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Implementation of a coal level sensing and control system comparing range sensor modalities

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Implementation of a Coal Level Sensing and Control System Comparing Range Sensor Modalities

by

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For this is the way, God loved the world: He gave his one and only Son, so that everyone who believes in him will not perish but have eternal life. For God did not send his Son into the world to condemn the world, but that the world should be saved through him.

BOC,
Ralph

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Abstract

Implementation of a Coal Level Sensing and Control System Comparing Range Sensor Modalities

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A coal-fired power plant typically has silos, bunkers or stockpiles in which the fuel is placed for storage purposes. Real-time feedback sensors are utilized to sense the coal height so data can be sent to downstream systems for further processing. These systems are required to accurately sense the height of coal within the bunker or stockpile. The range information is then fed in a real-time fashion to a control system. Inaccurate measurements can result in severe environmental and safety consequences. The coal-fired power plant application is especially daunting due to the particularly harsh operating conditions and reliability requirements. There are many types of ranging sensors available in the marketplace. The performance of ultrasonic, radar, and laser rangefinder sensors was investigated to determine the height of coal stockpiles in various sites in a coal-fired power plant. A system to control the spacing of a telescoping coal-delivery chute above its coal pile was designed (using the laser rangefinder), implemented, and tested. A detailed analysis of each sensor modality is provided, along with some conclusions regarding their performance. These systems are currently operational at a

plant located in northeast Texas. The ultrasonic and radar sensors were part of legacy systems and the new laser sensor was integrated as a part of this study. The feedback signals from each sensor were compared to measured data. The implementation of the laser rangefinders proved to be slightly more accurate than the other legacy systems. However, the laser rangefinder systems have some drawbacks that have been listed.

Chapter One

Introduction

Coal level detection and dust suppression are important in the operation of a coal-fired power plant. The coal must be transported from rail cars to the furnaces, via coal handling systems, while limiting emissions of airborne coal dust [1, 2]. A coal-fired power plant typically has silos, bunkers or stockpiles where the fuel is stored; various sensing modalities are used in practice to measure height of stockpiled coal in real time. The coal-fired power plant application is especially daunting due to the particularly harsh operating conditions and stringent reliability requirements. Real-time feedback sensors are utilized to sense the coal height so data can be sent to downstream systems for further processing. This thesis focuses on developing a position control system for a telescoping chute to maintain dust control on an unconstrained external coal stockpile. Laser-based systems were used to estimate the stockpile height and chute position. As a part of this research, coal level measurement data from two additional range sensor technologies already installed in the power plant environment was collected and compared to data obtained from the laser ranging system. The first two sensors were part of legacy systems and the laser system was designed, implemented and tested in the plant as a part of this effort. These systems determine the height of the coal and feed back the range data to their respective control systems in a real-time fashion thereby assisting with environmental, process and safety needs. All of the sensors were sourced off-the-shelf from different manufacturers, but have the same type of feedback control (4-20mA) into the control system. These systems are currently operational at a coal-fired power plant located in northeast Texas.

1.1 Coal Silo Handling Systems

The measurement of coal levels has always been a common issue in coal-fired power plants. Figure 1 below is an illustration of a typical layout of a coal handling system with ranging sensors at different points in the process.

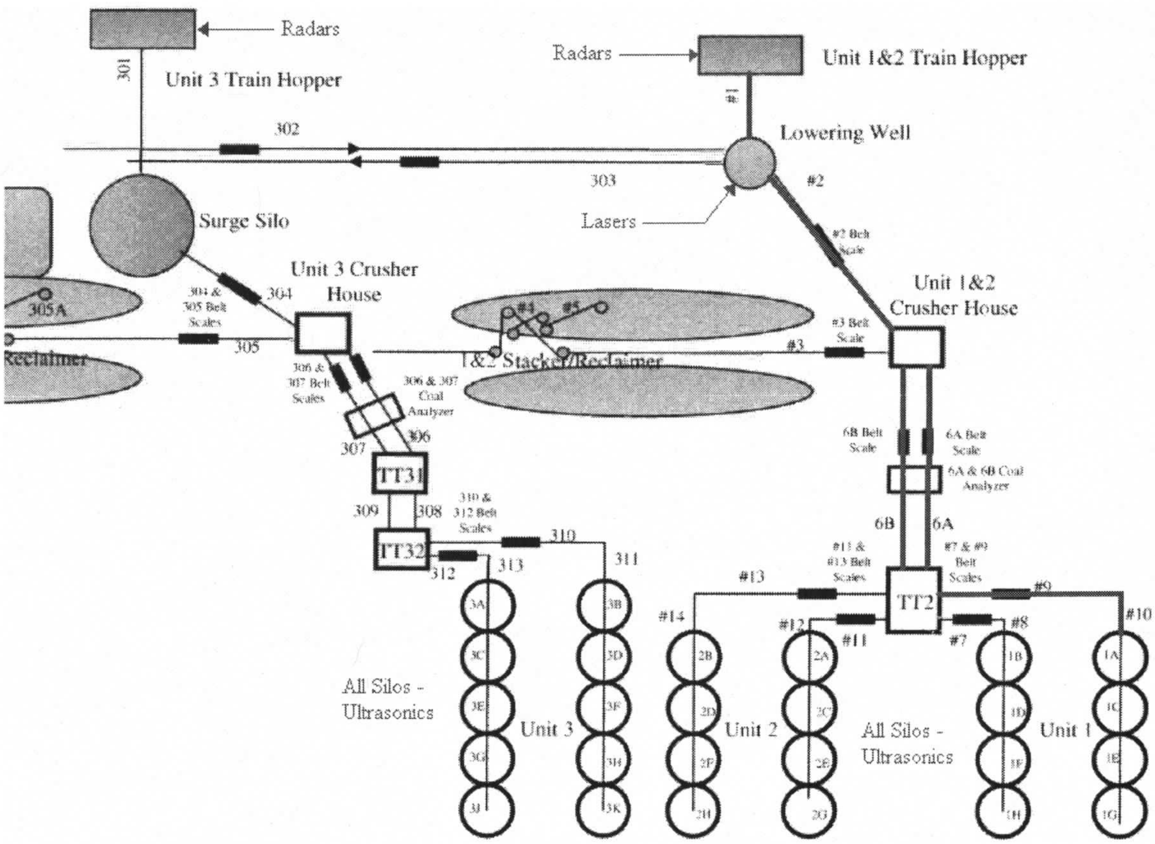

Figure 1. Coal Handling System Overview (Circles Represent Silos)

Redundancy is a key feature of this system. This is illustrated in Figure 1 with systems which interface Units 1 and 2 train hopper to Unit 3 train hopper. Thus coal can be delivered to any unit from either receiving station. A typical coal-handling operation sequence is described below with the assumption coal is being delivered to silo 1A of unit1.

- Coal is delivered to Unit 1 and 2 train hopper via rail car.

- Coal is transported via Conveyor #1 to a telescoping chute which transfers coal from Conveyor #1 to the lowering well.
- Coal is delivered to Unit1 and 2 crusher house via Conveyor #2, to be pulverized into smaller pieces.
- Coal is delivered to TT2 structure (Tripper House) via 6A and 6B conveyors.
- Coal is routed to Silo 1A via Conveyor #9.

Figure 2. Coal Silos

After coal is delivered to the silos, of which four are shown in Figure 2, the coal moves downward through feeder systems that control the coal flow at a uniform rate. The feeders maintain coal flow to another crusher machine called a bowl mill. Bowl mills crush the coal into a fine powder-like material. The pulverized coal is then blown into the boiler where it is ignited. Blowing the pulverized coal into the boiler is the function of the primary air system (PA Fans). If the coal level is not maintained in the coal silos, the primary air system can possibly force hot air back up through the coal silo and cause an explosion. This is referred to as a "blow-back" and is a danger to personnel entering and working in the tripper houses. Safety precautions must be observed when entering the tripper houses. It must be known that the coal level in the silo is sufficient to prevent blow-back before entry to the tripper houses may be allowed.

There are several points along the coal process in which ranging sensors are used to maintain a smooth flow of coal. The ranging sensors are located at the following locations:

- Unit 1, 2 and 3 Receiving Hoppers: Radar sensors determine material height in each rail car hopper.
- Lowering Well and Telescoping Chute: The telescoping chute receives coal from Conveyor #1. Coal drops through the telescoping chute onto a stockpile that sits atop the lowering well. Two lasers mounted on the telescoping chute are used for range-finding. One laser system determines the extension of the telescoping chute while the other detects height of the coal stockpile above the lowering well.
- Coal Silos: As shown in Figure 1, there are 26 silos located on three different coal-fired boilers. Ultrasonic range sensors determine height of the coal in each silo.

1.2 Objective and Framework

This thesis includes two parts: the primary focus is on design and implementation of a control system for the telescoping chute, while the secondary focus is a performance comparison of ground truth data in the form of actual coal levels with measured coal levels determined by legacy ultrasonic and radar systems.

1.3 Organization of the Thesis

This thesis is divided into five chapters. Chapter 2 discusses past work and background information about the laser control system and coal level measurement systems. Chapter 3 covers system implementation and control system interfacing details. Chapter 4 discusses performance of the range sensors. Chapter 5 details conclusions derived from the control system implementation and range sensor comparison results. Included in this project, are appendices with the raw data collected, electrical wiring diagrams, and software for the telescoping chute ranging system.

Chapter Two

Prior Work and Background

Coal-level sensing systems are used in power generation plants to sensed coal level heights. Power plants typically have sensor-based monitoring systems for failure detection [7]. Vendors have developed a wide variety of products and control system components that have been successfully used in power plants for performing equipment condition assessment and instrument calibration and monitoring [7].

As part of this research, three types of coal level sensors were investigated (ultrasonic, radar and laser) to determine which sensor is the best possible solution for sensing bulk material heights. The three systems are to provide continuous measurements of coal levels. The sensor data act as the input information to the control system, which makes calculations and decisions based on those data. The levels are continuously displayed on a Human Machine Interface (HMI).

2.1 Ultrasonic Ranging Systems

Ultrasonic range measurement systems are based upon transmitters and receivers in the ultrasound frequency range (20 kHz to 200 kHz) and are popular due to low cost [24]. There have been problems with the use of ultrasonic systems which have included the inability to make measurements in applications with dusty conditions, pressure fluctuations, changing angle of repose, large particle sizes, internal vessel obstructions, and coating or formation of clumps on the internal vessel surfaces. Some of these conditions can affect the way the sound wave reflects off the surface causing generation of false echoes that mask the true level signal. It is for this reason that there is a perception in the marketplace that ultrasonic systems require frequent recalibration to consistently meet performance requirements. It is also commonly believed that ultrasonic systems may not be reliable in dusty conditions. Many recent articles published in print and on the Internet indicate that newer technologies (like guided wave radar, air radar and laser systems) are supplanting ultrasonic units [8]. Some improvements in performance in dusty environments may be obtained by the use of low-frequency sensors (as low as 5 kHz). However, this may not be a universal solution as materials can absorb low frequency pulses rather than reflect them. Automatic gain control (varying the amount of amplification) and automatic power control (varying the strength of the transmitted pulse) help ultrasonic systems to maintain measurement accuracy if vessel conditions cause the reflected signal strength to fade during the process of filling or emptying. The use of digital signal processing (DSP) also provides a major improvement in performance. DSP and firmware with advanced algorithms process and analyze the return sound signal and make adjustments (increase the gain and/or power) as needed to maintain dependable measurements. DSP allows the system to take a "snapshot" of the local conditions in a vessel, record it to memory, and manipulate it. Digital filtering can average these echo profiles, and eliminate random interference sources to more reliably determine material level [8]. There is no doubt that state-of-the-art ultrasonic level systems have eliminated many of the problems exhibited by earlier designs, but there is still some doubt whether all problems, particularly those caused by heavy dust, have been satisfactorily dealt with by newer technologies. However, a high level of confidence exists in the reliable performance of a state-of-the-art ultrasonic system that has been approved by the manufacturer for specific applications under normal operating conditions [8].

2.1.1 Ultrasonic Theory of Operation

The system used to for the ultrasonic analysis is a Siemens Air Ranger XPL System. The XPL transmits electronic pulses to each scanned ultrasonic transducer which is setup in a planar array. The XPL system transmit pulse consists of one or more electrical "shot" pulses, which are supplied to a set of scanning relays. The scanning relays are the interface devices between the ultrasonic transducers and the XPL processor. The scanning relays act as a multiplexer to select the transducer (of the eight transducers in the XPL system) to be activated_. After each shot is fired, sufficient time is allowed for echo (shot reflection) reception before the next (if applicable) shot is fired. After all shots of the transmit pulse are fired, the resultant echoes are processed. Echo enhancement is achieved by removing noise and reforming the echo profile received. True echo selection is achieved by establishing the criteria which a portion of the echo profile must meet to be considered the true echo (echo reflected by the intended target). Insignificant portions of the echo profile outside of the measurement range are automatically disregarded. The remaining portions of the echo profile are evaluated using built-in algorithm(s) and short shot bias programming. When combinations of algorithms are used, the portion of the echo profile providing the best averaged echo confidence is selected as the true echo. True echo verification is automatically achieved by comparing the position (relation in time after transmit) of the "new" echo to the previously accepted echo position.

To calculate the round-trip transducer-to-material-level distance, the transmission medium (atmosphere) sound velocity is multiplied by the acoustic transmission-to-reception time period. This result is divided by 2 to calculate the one way distance.

$$d = \frac{v \times t}{2} \tag{2.1}$$

where:

d = distance from the transducer to the surface of the material, m.
v = sound velocity m/s.
t = reception time period, s.

The velocity of sound in the transmission medium is affected by the type, temperature, and vapor pressure of the gas(es) or vapor(s) present. Calibration of the ultrasonic ranging units assumes that transmission media is air at 20°C (68°F) and 101.3kPa (14.7psi). The sound velocity used for the distance calculation is 344.1 m/s (1129 ft/s).

2.2 Through-Air Radar Systems

Through-Air-Radar (TAR) for level measurement has become widely used in liquid and slurry applications. TAR is also becoming popular for harder-to-measure powder and bulk solids applications [8]. The radar energy is emitted into free space from an antenna and diverges as it propagates into the vessel. Some of the radar energy is reflected when the traveling electromagnetic wave encounters a change in characteristic impedance of the medium in which the wave is propagating (in level-measurement applications, this occurs when the traveling wave encounters the surface of the material being measured). As with ultrasonic level systems, internal vessel obstructions, changing angle of repose, and clumps of material adhering to the vessel walls can affect the reflected level signal and create artifacts [8]. Proper installation and setup is critical for good performance. State-of-the-art radar systems allow the user to map the vessel during setup to identify and eliminate false signal reflections. Some manufacturers require the use of a laptop PC with proprietary software for setup. This software incorporates all the experience gained in previous applications to discern the true level signal. Similar to ultrasonic systems, radar systems often use digital signal processing (DSP) and signal averaging techniques to successfully determine the level signal. TAR exists in two basic forms: pulsed (or time-of-flight) radar, and FMCW (frequency modulated continuous wave) radar.

2.2.1 Guided Wave Radar

Another type of radar system used in level measurement applications is Guided Wave Radar (GWR). These systems transmit electromagnetic energy along a waveguide probe in which the energy does not disperse [26]. GWR relies on the technique of Time Domain Reflectometry (TDR) to make distance measurements. In TDR, short pulses of electromagnetic energy are transmitted down the probe. When a pulse encounters the surface of a material whose characteristic impedance differs from that of free space, some part of the energy of the pulse is reflected. High-speed timing circuitry (measuring the time from the transmission of the pulse to the reception of the reflected pulse) provides an accurate measure of the distance traveled by the pulse and its reflection. GWR is useful for both liquid and bulk solid measurement applications. It has advantages compared with TAR because the energy transmitted through air by a TAR system diverges as it travels to the material surface and because the incident energy reflects irregularly from the material surface. The reflected energy is scattered in ways that are not predictable, and only that portion of reflected energy scattered back to the receiver can contribute to measurement. However, GWR systems are unsuited for use in coal-handling applications because of the susceptibility in their probes to physical damage.

2.2.2 Radar Theory of Operation

Radar level measurement uses the time of flight principle to determine distance to a material surface. The time of flight (TOF) principle represents a variety of methods that measure the time required for an object, a particle, or an acoustic, electromagnetic or other wave to travel a distance through a medium. This measurement can be used for a time standard, as a way to measure velocity or path length through a given medium, or as a way to learn about the particle or medium (such as composition or flow rate). The traveling object may be detected directly (e.g., ion detector in mass spectrometry) or indirectly (e.g., light scattered from an object in laser Doppler velocimetry) [25]. For this application, the coal for all intents and purposes is considered stationary.

There are two means of determining time-of-flight in radar systems: pulsed radar and FMCW radar. FMCW radar transmits a continuous wave whose transmitted frequency is modulated in a repetitive pattern. The transmitted signal is mixed with the signal reflected from a target, and the distance between the transmitter and target is determined from the difference in transmitted and reflected signal frequencies. FMCW ranging for a sawtooth waveform is given in the following set of equations:

$$k = \frac{\Delta f_r}{\Delta t_s} \tag{2.2}$$

where:

k = radar sweep rate, s^{-2}

Δf_{r}= radar frequency sweep, Hz;

Δt_s = period of the radar frequency sweep, s.

Let t_r be defined as the round-trip time of the radar signal measured in seconds and Δf_{echo} be the difference between the instantaneous frequencies of the transmitted signal and the echo (reflected signal). The round-trip time for the radar signal, t_r, is then given by:

$$t_r = \frac{\Delta f_{echo}}{k} \tag{2.3}$$

The time of flight is thus proportional to the difference in frequency between the transmitted and received signals. Electromagnetic wave propagation is virtually unaffected by temperature or pressure changes, or by changes in the vapor or dust levels inside a vessel. The one-way distance (d_o) may be calculated as follows:

$$d_o = \frac{ct_r}{2} \tag{2.4}$$

where:

c = speed of light in the medium of propagation (3.0×10^8 m/s in vacuum or air).

The radar system used for this project is the Siemens LR460. The LR460 consists of an enclosed electronic component coupled to an antenna and process connection. The electronic component sweeps a carrier frequency from 24.2 GHz to 25.2 GHz that is directed to the antenna [5]. The signal is emitted from the antenna, and the reflected echoes are digitally converted to an echo profile. The profile is analyzed to determine the distance from the material surface to the reference point on the instrument. The profile is user definable and can be modified dependant upon the response needed with respect to the material being measured.

2.3 Laser Systems

Laser ranging systems have traditionally not been used extensively due to cost considerations. The laser is a narrow beam that does not scatter on reflection due to the laser beam is so small that the reflecting surface is essentially planar. It is easy to aim, particularly around internal obstructions in the vessel, and easy to set up. Lasers can be mounted inside a vessel, or if process conditions are too extreme, can be mounted outside and aimed through an appropriate sight glass installed in the top of the vessel. Manufacturers state that lasers can penetrate dust. However, the laser lens needs to be kept clean. Laser systems do offer pinpoint accuracy for measuring level. Their accuracy is particularly superior to other systems for ranges over 15 meters. These units are non-invasive, highly accurate and respond quickly to changes in material level. If true continuous measurement is needed they are a good option. They are however, more expensive than the other two ranging technologies.

2.3.1 Laser System Theory of Operation

The key element of the laser transmitter is a small semiconductor laser, also known as diode laser or injection laser. The semiconductor laser converts electrical energy (a current pulse) into optical energy (the optical pulse) with high efficiency and high reliability over a wide range of ambient temperatures.

The amount of light that is reflected from a target's surface is characterized by the reflectivity coefficient. Reflectivity is the ratio of the energy density carried by a wave which is reflected from a surface to the energy density carried by the wave which is incident on the surface. For a diffusely reflecting target, the maximum value of reflectivity is 100%. The reflectivity can be greater than 100% for materials having shiny or glossy surfaces when illuminated with an incident beam perpendicular to the material surface. The reflectivity coefficient is also a function of the wavelength. Diffuse reflection signals are reflected omnidirectionally according to Lambert's cosine law [6]. Mirror-like reflection signals have the same angle of incidence with respect to the target surface as the transmitted signal, with the incident beam and reflected beam lying in the same plane [6]. Light reflected from retro-reflectors are returned in the same direction as the incident beam over a wide range of angles of incidence. This property is maintained over a wide range of directions of the incident beam. It should be noted, for retro-reflecting targets the reflectivity is not always perfect. A perfect diffusing reflecting target has 100% reflectivity and reflects back into the whole half space. However, if the light is reflected back into a smaller angular sector, as with mirrors, the reflectivity can be greater than 100%. Listed in Figure 3 are some reflectivity coefficients for various surfaces and materials [6].

Diffusely reflecting surfaces/materials1)	
Material	Reflectivity
White Paper	up to 100%
Dimension lumber (pine, clean, dry)	94%
Snow	80-90%
Beer Foam	88%
White Masonry	85%
Limestone, clay	up to>75%
Newspaper with print	69%
Tissue paper, two ply	60%
Deciduous trees	typ. 60%
Coniferous trees	typ.30%
Carbonate sand (dry)	57%
Carbonate sand (wet)	41%
Beach sands, bare areas in desert	typ. 50%
Rough wood pallet (clean)	25%
Concrete, smooth	24%
Asphalt with pebbles	17%
Lava	8%
Black neoprene	5%
Black rubber tire wall	2%
Glossy, mirror-like or retroflecting surfaces1)	
Material	Reflectivity
Reflecting foil 3M2000X	1250%
Opaque white plastic2)	110%
Opaque black plastic2)	17%
Clear plastic2)	50%

Figure 3. Reflectivity Coefficients for Common Materials

Notes:

1) Values of reflectivity are given for a wavelength of about 0.9 micrometers.
2) For materials with shiny or glossy surfaces, the reflectivity figure represents the maximum light return, with the incident sensor beam perpendicular to the material surface.

2.4 Real Time Control System

In 2008, the engineering team at the Monticello Steam Electric Station was presented with the task of automating the downward movement of a telescoping chute, shown in Figure 4, in order to prevent airborne dust particles from rising up out of this system and escaping into the environment. The theory of operation is to keep the telescoping chute as close to the stockpile as possible without overdriving into the stockpile and also move the chute upward when the stockpile increases in height. This would keep airborne dust down to a minimum which would meet or exceed environmental and health expectations.

The main reason to install a level detection system was to automate the downward movement of the telescoping chute. Before this project was implemented, the downward movement of the telescoping chute was controlled manually from a remote location. If an operator was not available to move the telescoping chute when the system was ready to unload, the gap between the telescoping chute and the coal pile would allow a dust plume to escape and cause environmental concerns.

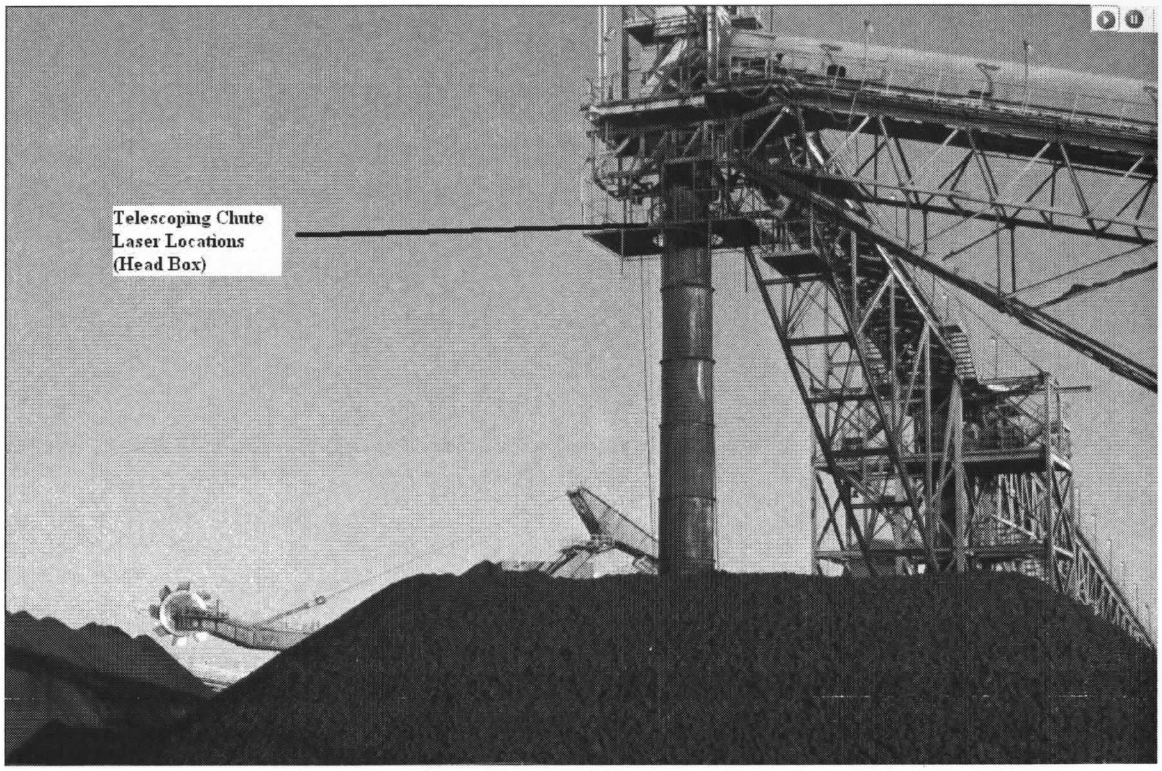

Figure 4. Telescoping Chute Above an Unconstrained, Open Air, Coal Pile

The upward movement was already automated through operation of tilt-probes mounted on the end of the chute. Before the laser system implementation, the telescoping chute could only be manually lowered to close proximity of the stockpile and usually was lowered until a tilt probe made contact with the stockpile. One of the criteria for the project was not to override any existing control logic including the upward movement function. Therefore, the laser system had to interface with existing controls, but not remove or interfere with existing logic functions.

In order to complete this project, a suitable device had to be selected that would sense both the positions of the telescoping chute and the height of the stockpile while operating in a hostile environment. A number of solutions were considered for this project including tilt probes, radar, ultrasonics, encoders, resolvers and a laser distance system. The decision from engineering reviews was to implement two laser systems, one for measurement of the stockpile and one for the telescoping chute position. This coal stockpile is located at the lowering well and is not confined within a silo, bin or hopper.

The problem is compounded by a non-linear stock-pile decay like that shown in Figure 5. There are two types of coal shown in Figure 5. The coarser coal (upper left) is lignite, and the finer coal (middle right) is Powder River Basin (PRB) coal. Lignite coal is the lowest-rank coal with a heat value of less than 19.4 MJ/kg (8300 Btu/lb) [1]. PRB is classified as sub-bituminous coal and has a heat value of approximately 19.4MJ/kg to 26.7MJ/kg (8300 to 11500 Btu/lb) [1]. Even though there are different types of coal shown in the picture below, this is only partially responsible for the way the coal pile decays. The primary cause of the uneven decay of the stockpile is the lowering well feeder system below the stockpile. There are four lowering well feeders as illustrated in Figure 5 and 6 and they do not feed out at the same rate. Furthermore, it is difficult to predict geometry of decay. To account for the previously described non-linear, asymmetric, pile geometry, a stockpile profile curve was developed to track movement of the chute in relation to the stockpile. A function generator in the control software was utilized to generate the profile curve and the values for the curve were based upon experimental results. The profile curve may be programmed through the Human-Machine Interface (HMI). There are four lowering feeders as illustrated in Figure 6, and they do not feed out at the same rate. The asymmetric lowering well feeder geometry, compounded with the random mix of lignite and PRB, each with different adhesion characteristics, prevents using angle of repose theory to form a predictive model of the coal height based on a single-point measurement. Some form of empirical model would be required, and was subsequently developed for the chute position control system.

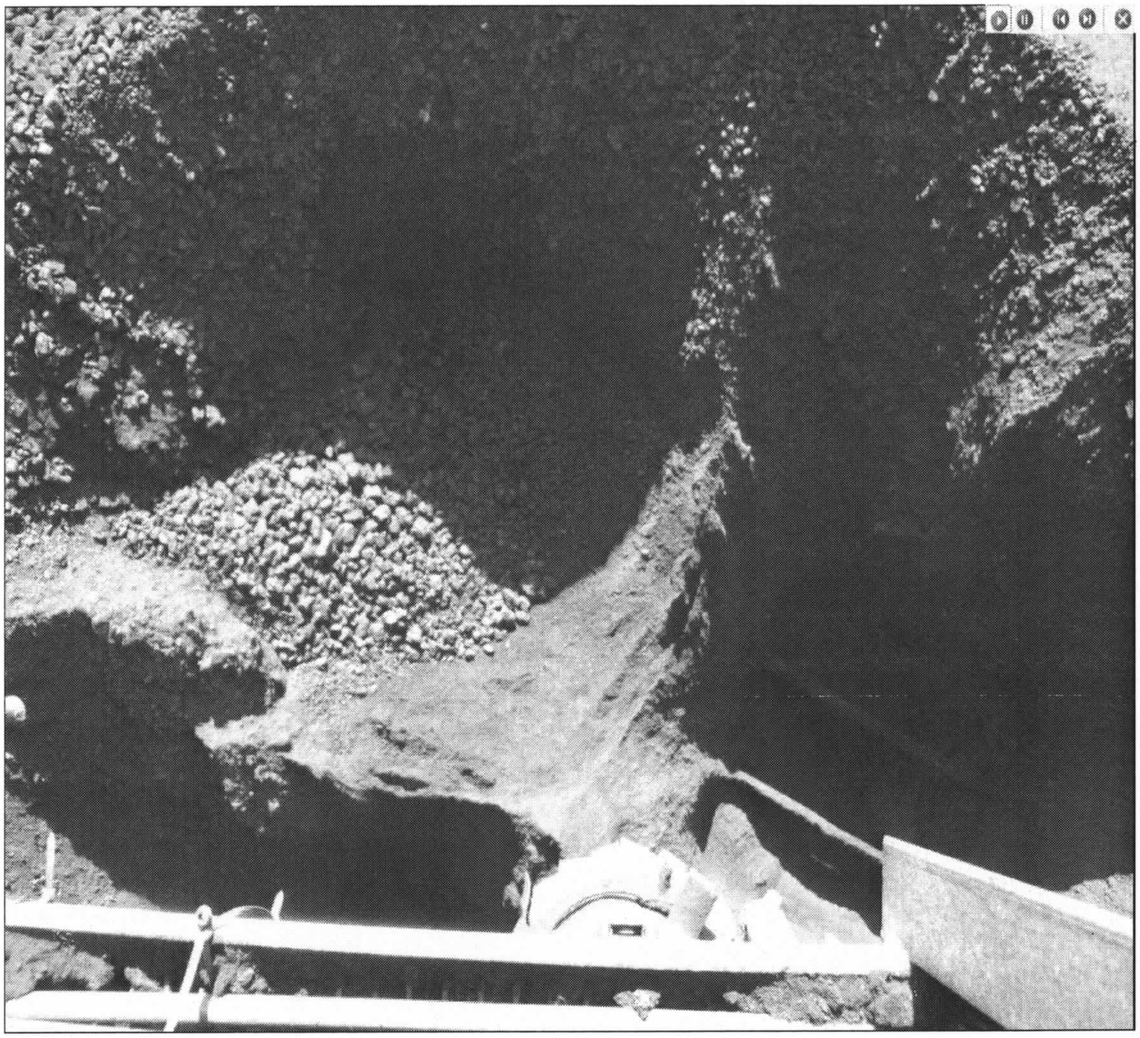

Figure 5. Telescoping Chute Stockpile – Lignite Left, PRB Right

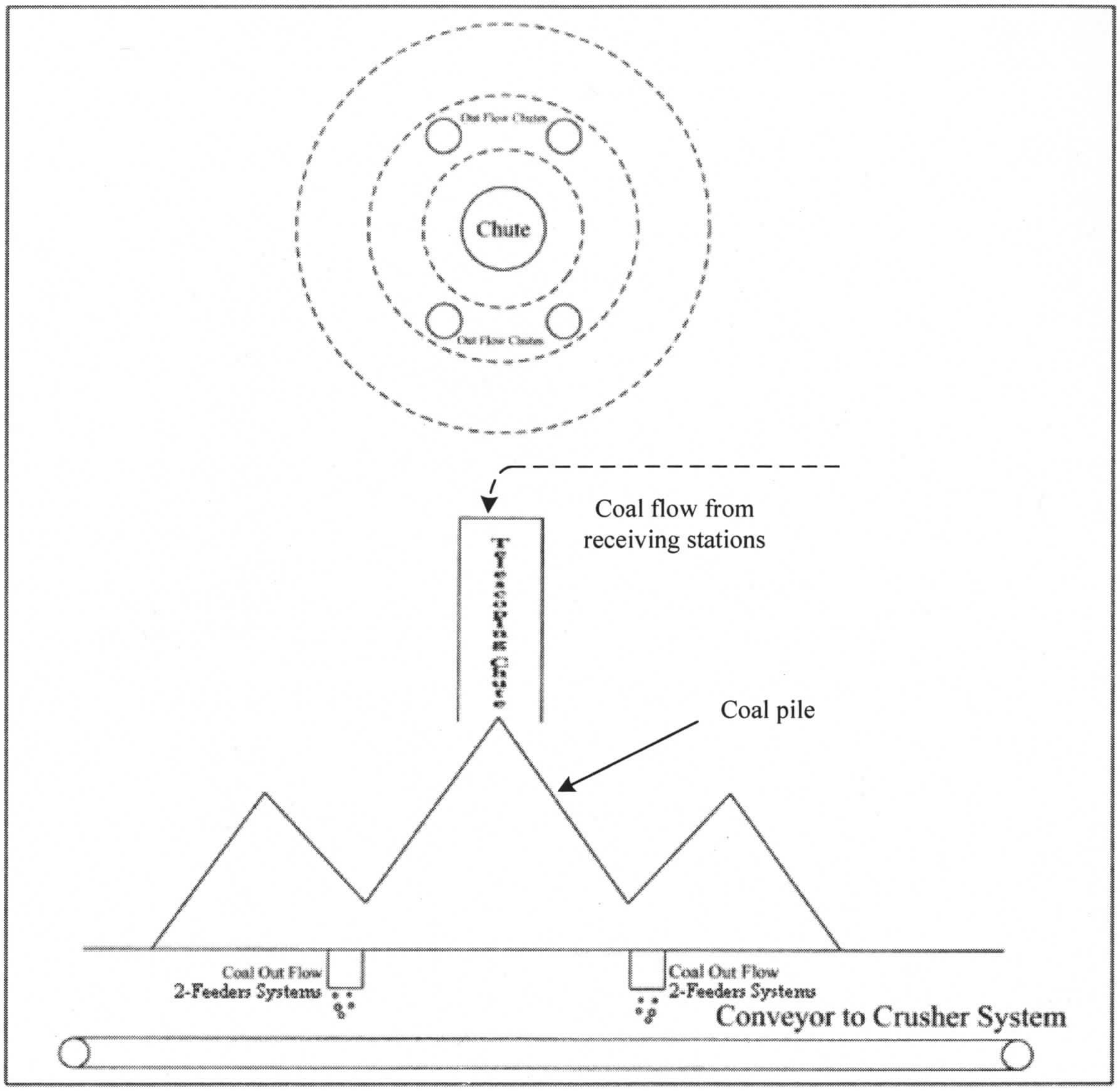

Figure 6. Telescoping Chute Process Illustration

2.5 Angle of Repose

An important parameter while measuring levels in silos or stockpiles is the angle of repose. The angle of repose is an engineering property of granular materials. It is the maximum angle of a stable slope determined by friction, cohesion and the shapes of the particles [4]. An example of angle of repose is shown in Figure 7:

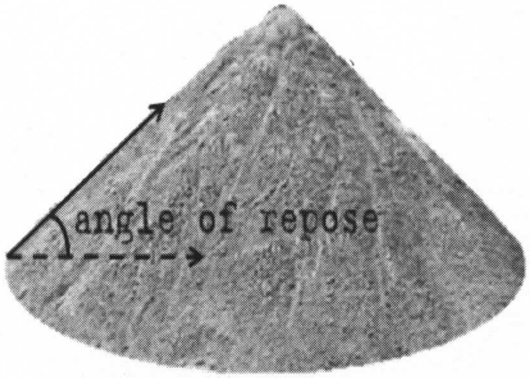

Figure 7. Angle of Repose

Solids stored in a vessel do not have a flat, horizontal surface like liquids. The surface of a pile of powder and granular material manifests an angle of repose. The angle of repose, or shape of the surface, can vary widely depending upon the manner and location(s) of fill and removal [4]. Additionally, there are other physical issues such as ratholing and bridging that cause problems within coal silos and stockpiles. Ratholing is a phenomenon in which holes or pockets are form within the coal and can shift the height of the coal once the pocket collapses. Bridging may occur in vessels filled with materials such as coal that readily absorb or trap moisture; the moist material may cake or clump inside the vessel and form bridges or arches. The accuracy of a level measurement system for bulk solids applications is the stated accuracy of the manufacturer, usually stated in terms of distance or level [6], but can be greatly affected by these other physical phenomena that cause granular materials to significantly deviate from the angle of repose behavioral model.

Chapter Three

Control System Design

This thesis focuses on developing a position control system for a telescoping chute to maintain dust control on an unconstrained external coal stockpile. Laser-based systems were used to estimate the stockpile height and chute position. As a part of this research, coal level measurement data from two additional range sensor technologies already installed in the power plant environment were collected and compared to data obtained from the laser ranging system. Sensor performance is based on a single parameter which is measurement error. The range sensors were ultrasonic, radar and laser systems. Each ranging system will be introduced in this chapter. Additionally, significant control functionality of the telescoping chute control system will be described.

3.1 System Descriptions

The following sections provide specifics about each of the systems mentioned above.

3.1.1 Ultrasonic Systems

The ultrasonic systems are used in the coal silos. In Figure 2, the range systems that are mounted at the top of the silos are Siemens Milltronics XLT ultrasonic ranging systems. These systems have been in operation at the Monticello Generating Station since 2003. In this project, performance analysis was conducted on this sensor and compared to the other two types of sensors.

The Milltronics Airanger is a non-contact ultrasonic level measurement system comprised of an ultrasonic signal transducer and a remotely-mounted electronic transceiver [3]. The transducer emits a continuous series of ultrasonic pulses and receives the reflected echoes on the round trip from the liquid or solid surface being monitored [4]. The microprocessor in the transceiver converts the signals into distance, level or volume (if dimensions are known), and displays data as an LCD digital readout [3]. In an ideal process, there would be a single strong return signal from the reflecting surface, and monitoring the level of a liquid or solid in a vessel would be a simple process. But in reality, there are many complicating factors. Turbulence, dust, steam, echoes from false targets like ladders, beams or pipes, and attenuation with distance are just a few of the many elements that can compromise the performance of the ultrasonic rangefinder. [4]. The transducers are hermetically sealed during manufacturing and are used to monitor levels of extremely hot corrosives and chemicals up to temperatures of 145°C (293°F) [3]. With applications that require maximum acoustic power in hot, wet, dusty conditions, four XPS series transducers can be used to measure materials as diverse as fly ash, lime, or bauxite slurry. These systems can perform in harsh environments at temperatures up to 95°C (203°F) [3]. These heavy duty transducers operate effectively at ranges to 60m (200 ft.) in liquids and solids in hot (up to 150°C/302°F) hostile environments, a major advantage for difficult applications like cement and wood pulp [3].

3.1.2 Radar Systems

The radar guided systems being evaluated are mounted at the top of a coal bunker called the Train Receiving Hopper as illustrated in Figure 8. The Train Receiving Hopper is the first entry point for coal arriving at the plant. Coal is delivered to the Train Receiving Hopper from rail cars. The coal is then conveyed to the power plant through coal handling systems. The objective of the radar system is to the coal height so that a small level of coal can be maintained to protect the feeder systems below the hopper. A small level in the hopper provides a buffer from falling coal and prevents damage to the feeder systems. Additionally, the radars can give operators coal height indication and possibly prevent coal rising into the rail car which has caused derailments.

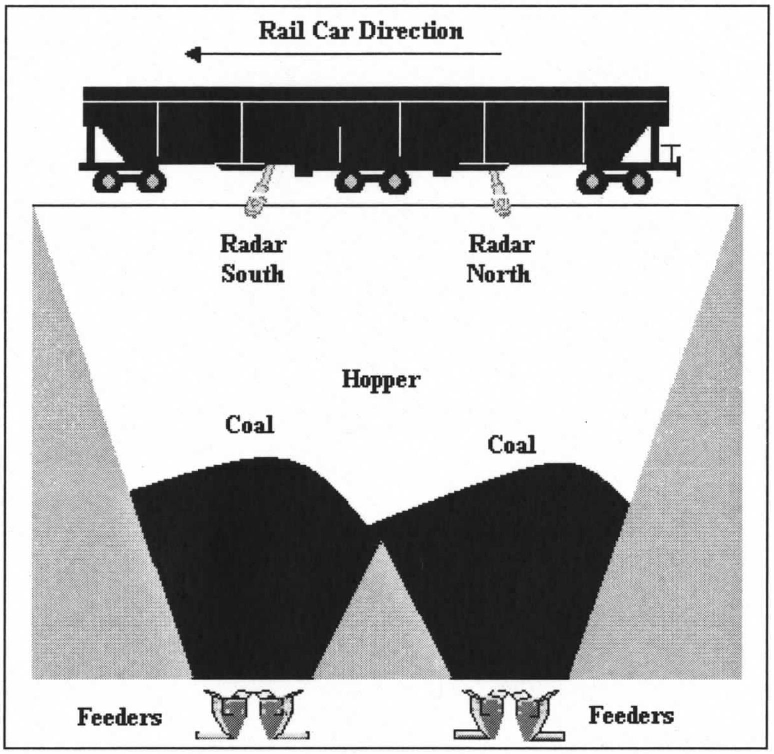

Figure 8. Train Receiving Hopper Illustration

The hopper, which is directly below the rail car shown in Figure 8, is 11.5m (38ft) deep. Below the hoppers are feeder systems that will move coal to another transfer point such as the telescoping chute shown in Figure 4. The radar systems are mounted on the opposite side of the rail cars. There are two hoppers, and one radar sensor is mounted in the top plate of each hopper.

For this coal-fired power plant, the Siemens LR 460 radar system is utilized. The Siemens LR460 is a 4-wire 24 GHz FMCW (Frequency Modulated/Continuous Wave) radar level transmitter with extremely high signal-to-noise ratio and advanced signal processing for continuous monitoring of solids up to 100 meters (328 ft) [5]. This system has an aimer design which makes it easy to install the device and orient the signal towards the material angle of repose [5]. The high frequency signal creates a narrow antenna pattern, which makes the LR 460 quite insensitive to vessel interferences. The feed-horns are aimed towards the cone section of the hoppers. The LR 460 is 120VAC powered and for this application utilizes a 4-20mA output signal into an Allen-Bradley PLC5 control system.

3.1.3 Laser System

In Figure 9 below, is a block diagram of the laser level control system. Two lasers were installed, one to detect the telescoping chute position and one to detect the stockpile height. The laser rangefinders produce a 4-20mA output signal to indicate distance. The laser rangefinders are under the control of an Allen-Bradley ControlLogix based system. This system controls two racks; one being a master control rack and one remotely mounted slave rack. The master control system has a rack-mounted Allen-Bradley ControlLogix processor and controls the slave control system via Ethernet/Wireless/Ethernet. A second processor was not installed at the slave location to minimize cost, but the slave rack does have an Ethernet interface into the master rack via a wireless link. The wireless radios used for this implementation were Phoenix Contact 2.4 GHz Ethernet radios configured to operate with the 802.11g protocol. For this application, wireless radios were chosen to avoid long cable lengths between the master and slave control systems.

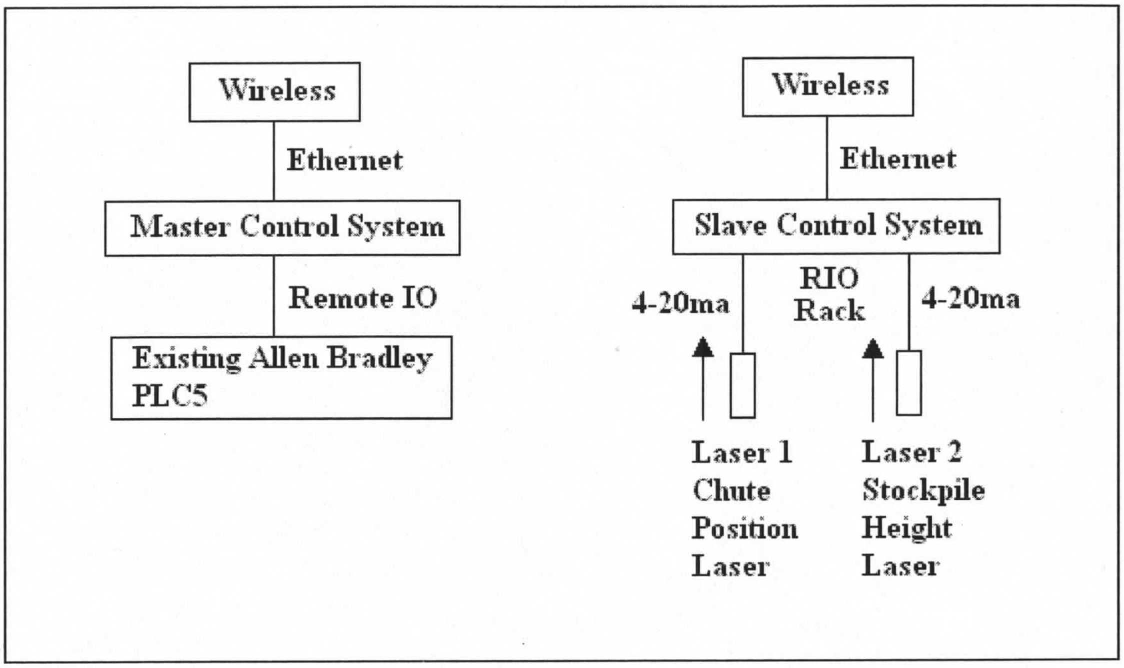

Figure 9. Block Diagram of Laser Range System

The design requirements for project implementation included interfacing with the existing control system network, which is an Allen-Bradley Universal Remote I/O (RIO) network, to laser control system. This would provide a network gateway between the laser control system and the existing legacy PLC5 system. In order to interface the laser master rack to the existing control system, the PLC5 has to be in control of the laser master rack due to the architecture requirements of the RIO. The RIO network is a master-slave network configuration in which there can only be one master station. Since there can be only one master station, the PLC5 has to be master control over the ControlLogix system. If the ControlLogix system were to be the master control station of the RIO network, a major reorganization of the RIO architecture would have to be completed at a high cost.

The laser systems that are installed on the telescoping chute (Figure 4) are two Riegl LD90-450 systems. The Riegl LD 90-450 is a high-reliability sensor for industrial use either in reflectorless applications or with retro-reflecting targets [6]. As mentioned previously, the telescoping chute is a cross-over point that will transfer coal from either a rail system or from other units. The main task of this project was to automate downward movement of the telescoping chute. The two Riegl LD90s are mounted on the telescoping chute at the lower elevation (see Figure 4): one to sense the height of the stockpile and one to sense the position of the telescoping chute. The specific laser systems were chosen for this project based on observations at other coal-fired power plants where they have proven to be reliable and virtually maintenance free. Figure 10 below from the manufacture's literature illustrates the basic operation of the LD90-450 [6]. The transmitter is a semiconductor diode laser sending out infrared light pulses, which are collimated by the transmitter lens [6].

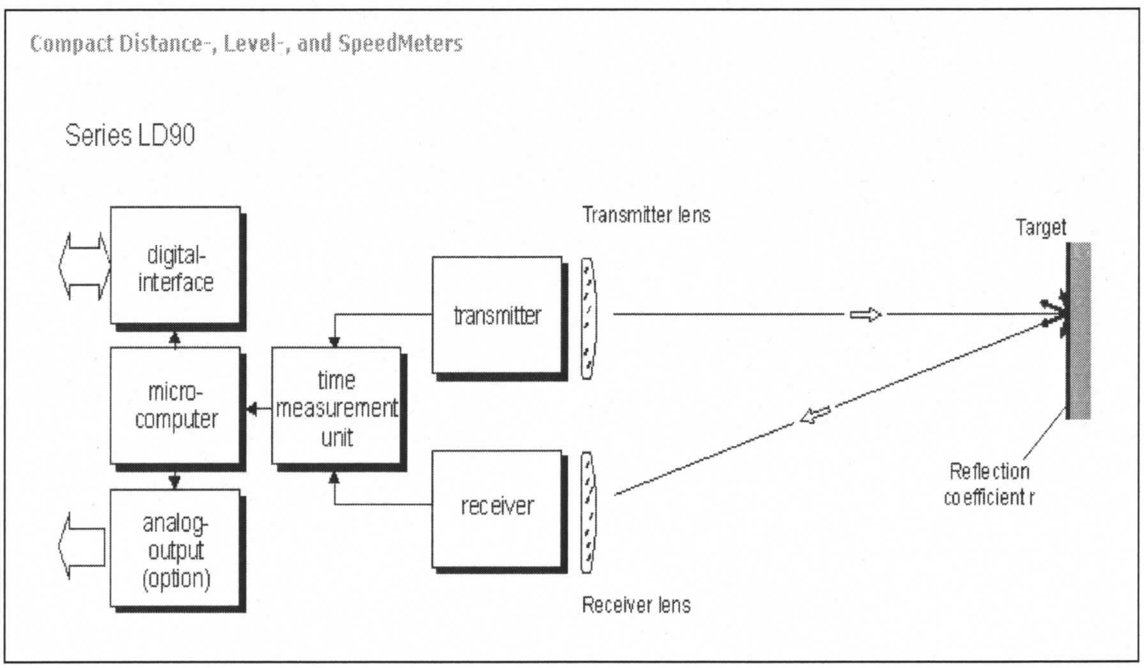

Figure 10. Basic Operation of the LD90-450

A portion of the signal reflected by the target is focused by the receiver lens on a photodiode which generates a corresponding electrical signal. The time interval between the transmitted and received pulses is counted by means of a counter with stabilized clock frequency. The calculated value is fed into the internal microcomputer which processes the measured data and prepares it for range and speed display as well as for data output. The data output can be either a serial interface or 4-20mA analog feedback signal [6].

3.2 Telescoping Chute Control System

The system used to automate downward movement of the telescoping chute is a ControlLogix-based system. The ControlLogix platform (available from Allen-Bradley, a subsidiary of Rockwell Automation, Inc) is classified as a Programmable Automation Controller (PAC) [9, 13]. RSLogix 5000 (Rockwell Software, Inc.) is the software programming package for the ControlLogix platform. RSLogix 5000 utilizes function blocks, ladder logic, and other basic tasks.

3.3 The Laser Control System Architecture

In Figures 11 and 12 are the ControlLogix racks used to implement the laser system. Figure 11 is a photograph of the laser ControlLogix master rack and Figure 12 is a photograph of the laser remote slave rack.

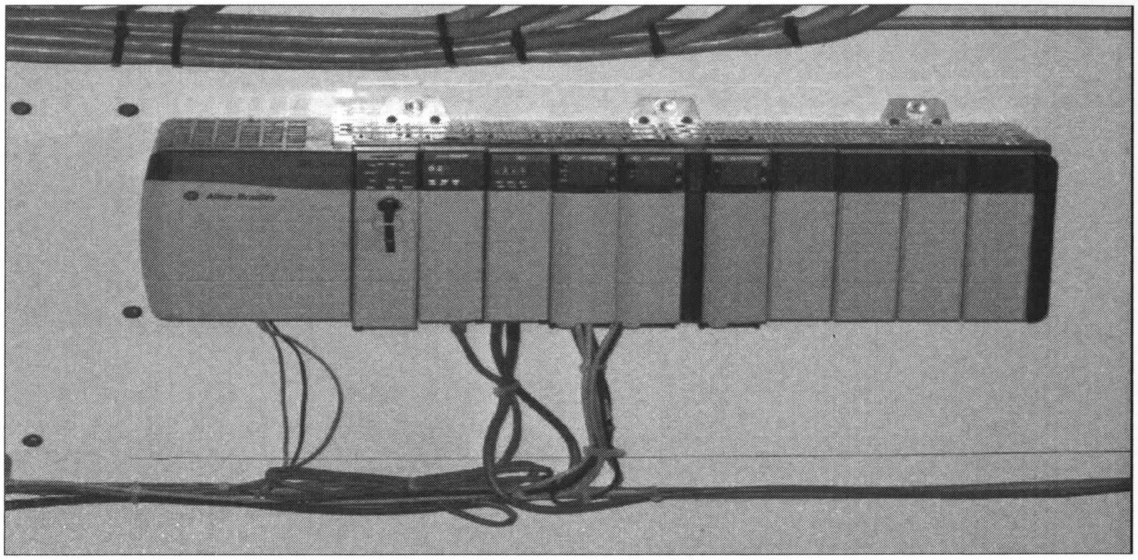

Figure 11. Laser Control System Master Rack

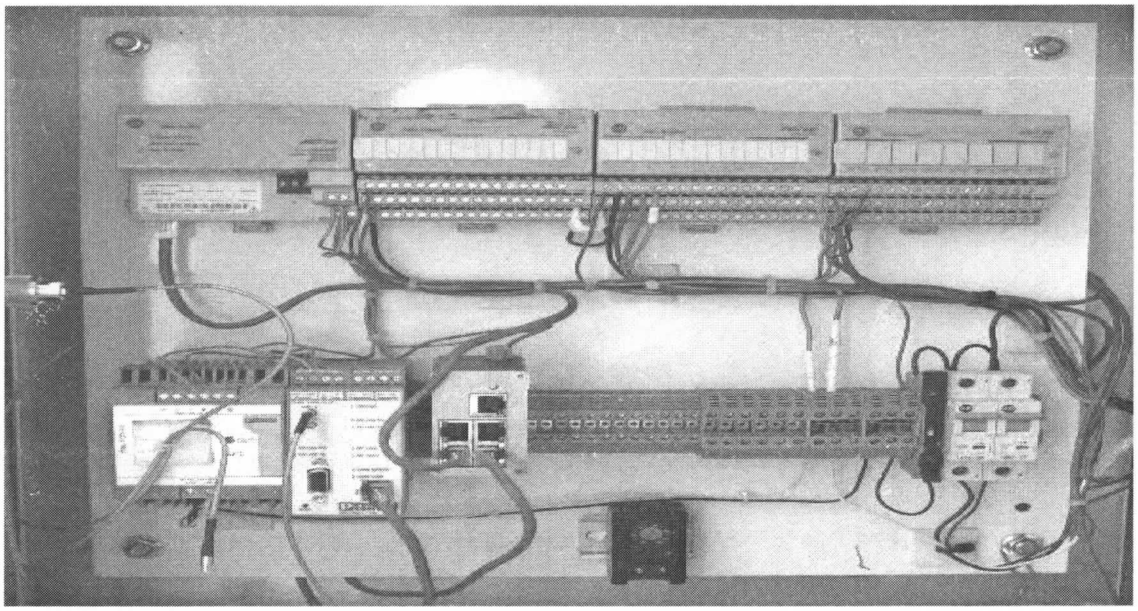

Figure 12. Laser Control System Slave Remote Rack

The slave rack is used to interface the laser analog feedback (4-20mA) from the lasers to the master rack. The master rack and the slave rack communicate via Ethernet link [12]. Wireless communication was chosen to eliminate the need for cabling between the master and remote racks which are separated by about 300 meters. A list of the cards used to complete the laser project is provided below:

ControlLogix Rack – Master Rack

- ControlLogix L61 Processor – Main Processor, in slot 0 of master rack [20].
- ControlLogix Ethernet 10/100MB Bridge – Ethernet Card, slot 1 [21].
- ControlLogix Remote IO Interface Card – Remote IO, slot 2 [19].
- ControlLogix AC Output Card – 120VAC Output Card, slot 3 [14].
- ControlLogix AC Input Card – 120VAC Input Card, slot 4 [19].
- ControlLogix Relay Out Card – Relay Contact Output Card, slot 5 [17].

Remote Rack – Slave Rack

- Flex Remote IO ASB adapter – Ethernet Interface to Master Rack [22].
- Flex Remote IO AC Output Card – 120VAC Output, module 0 [16].
- Flex Remote IO AC Input Card – 120VAC Input, module 1 [16].
- Flex Remote IO Analog Input Card – 4-20ma, receives laser feedback, module 2 [16].

RSLogix 5000 has several different routines that operate within the structure of the program. These routines are ladder (Figure 13), function blocks (Figure 14), structure text and sequential function charts. Ladder and function block routines were implemented as a part of the control system.

Ladder routines are structured just as the name implies: routines that scan from the top down, and left to right – similar to descending a ladder. The ladder elements, called rungs, may or may not have conditional elements that determine the state of the output as shown in Figure 13 [10]. Many types of instructions can be used in ladder routines such as input contacts from relays and outputs to relay coils.

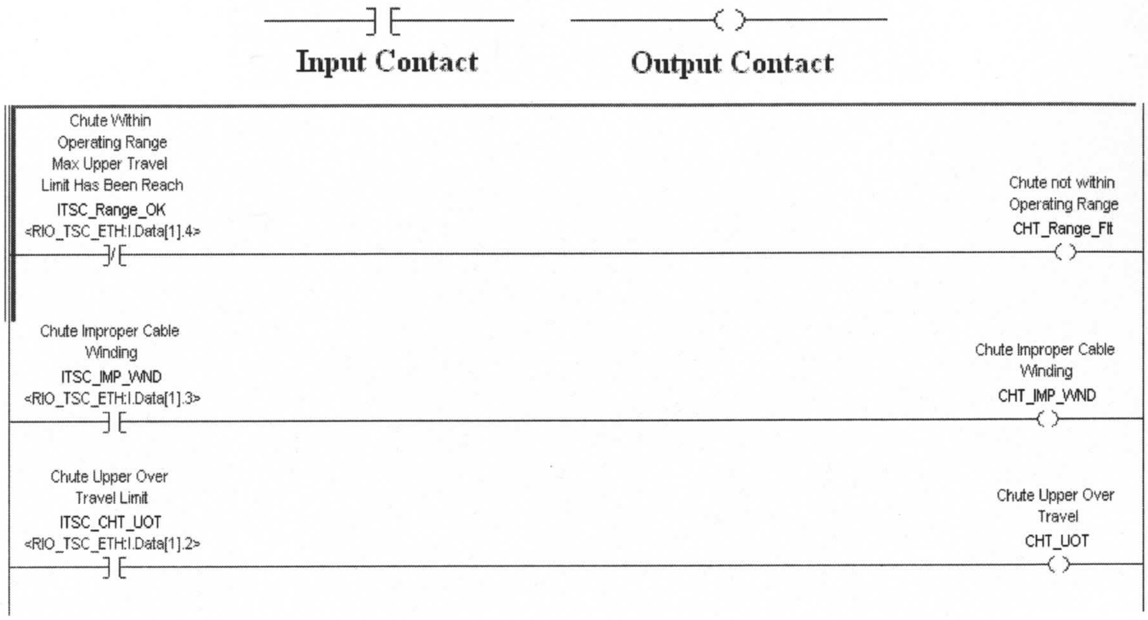

Figure 13. Laser Control System Ladder Routine Example

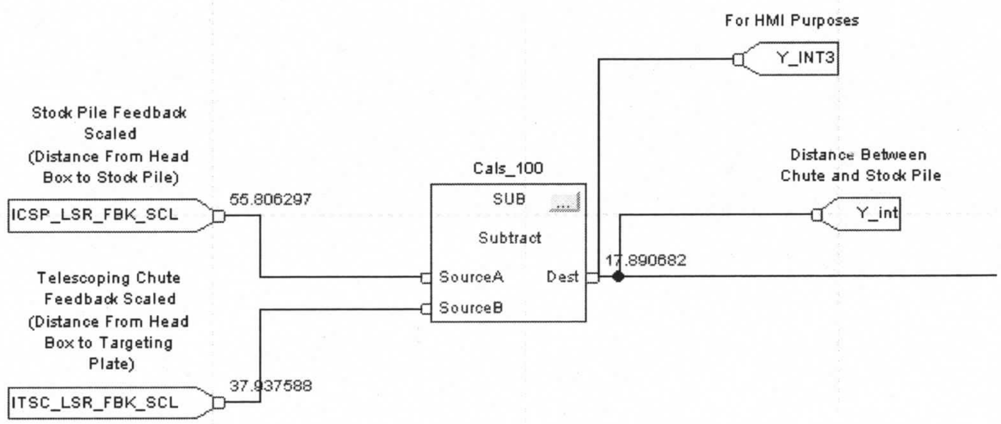

Figure 14. Laser Control System Function Block Example

Function block routines are more complicated than ladder routines and an illustration of a subtract block is shown Figure 14. However, more functions can be accomplished with function blocks and there are many pre-built function blocks within the RSLogix 5000 and ControlLogix platform. The RSLogix 5000 programming software automatically determines the order of execution for the function blocks in a routine when the processor [11]:

- verifies a function block routine
- verifies a project that contains a function block routine
- downloads a project that contains a function block routine

The execution order is defined by wiring function blocks and indicating the data flow of any feedback wires, if necessary. If function blocks are not wired together, it does not matter which block executes first [11]. There is no data flow between the blocks. If the blocks are wired sequentially, the execution order moves from input to output [11]. The inputs of a block require data to be available before the controller can execute that block.

The purpose of the telescoping chute is to move in close proximity to the stockpile, thereby suppressing dust and protecting equipment below the chute.

The Laser System electrical wiring diagram is shown in Figure 15, 16 and 17. Lasers are powered with 120VAC and provide a 4-20mA signal output to the control system. The control system shown in Figure 16 has a wireless connection between the lasers and the master rack. The main control system is an Allen-Bradley ControlLogix system which is shown is Figure 11 and the slave rack is shown in Figure 12. The master rack has control of the laser feedback by utilizing a ControlLogix processor located in slot 0. Additionally, the laser feedback is wired into an analog input card, which is shown in Figure 17. The analog input card is slot 2 of the slave rack. The two tags on the analog input card are the input tags assignments (variables) in the ControlLogix system. The laser feedback is a loop-powered 4-20mA circuit. A complete set of the electrical prints are provided in Appendix B.

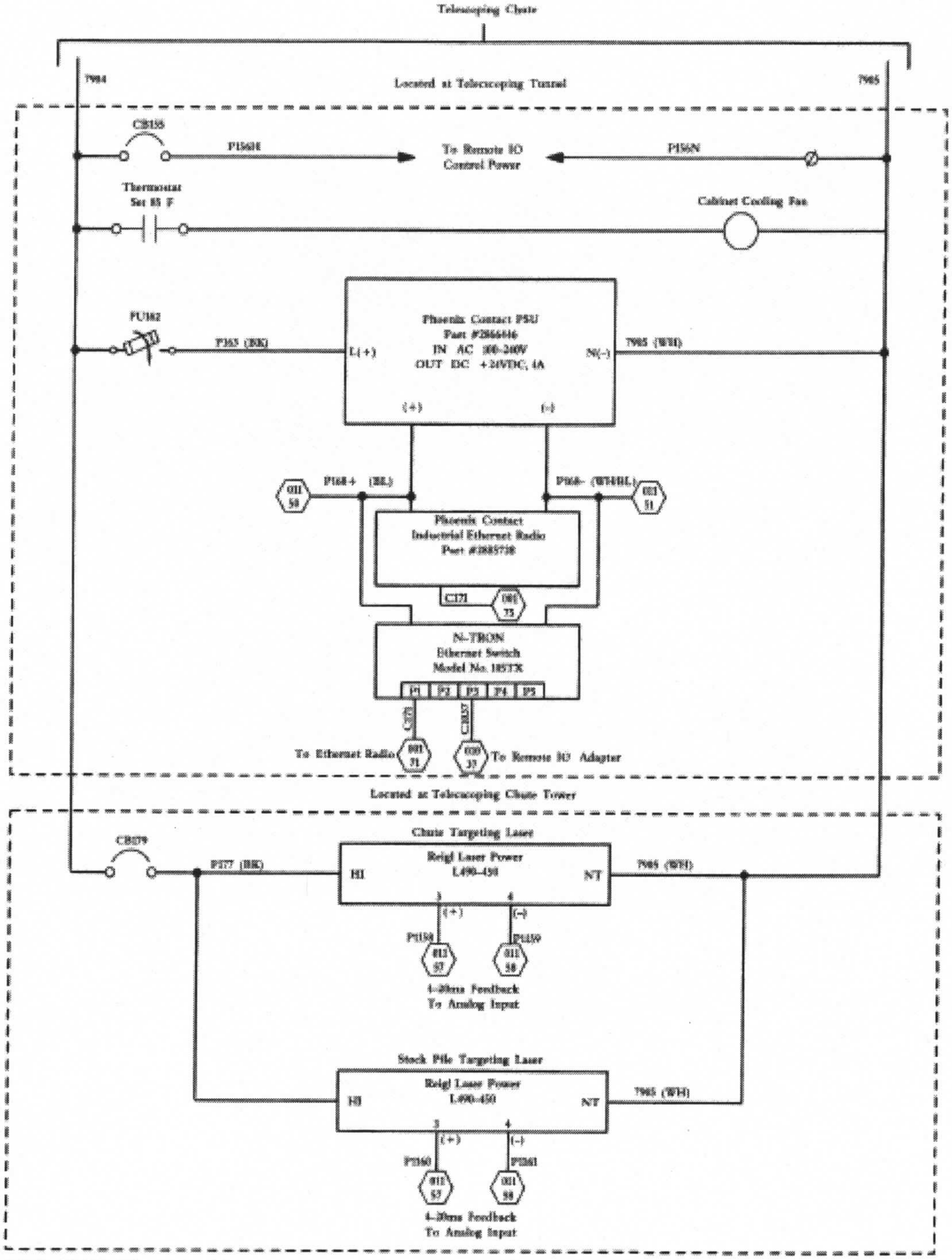

Figure 15. Laser Wiring Diagram

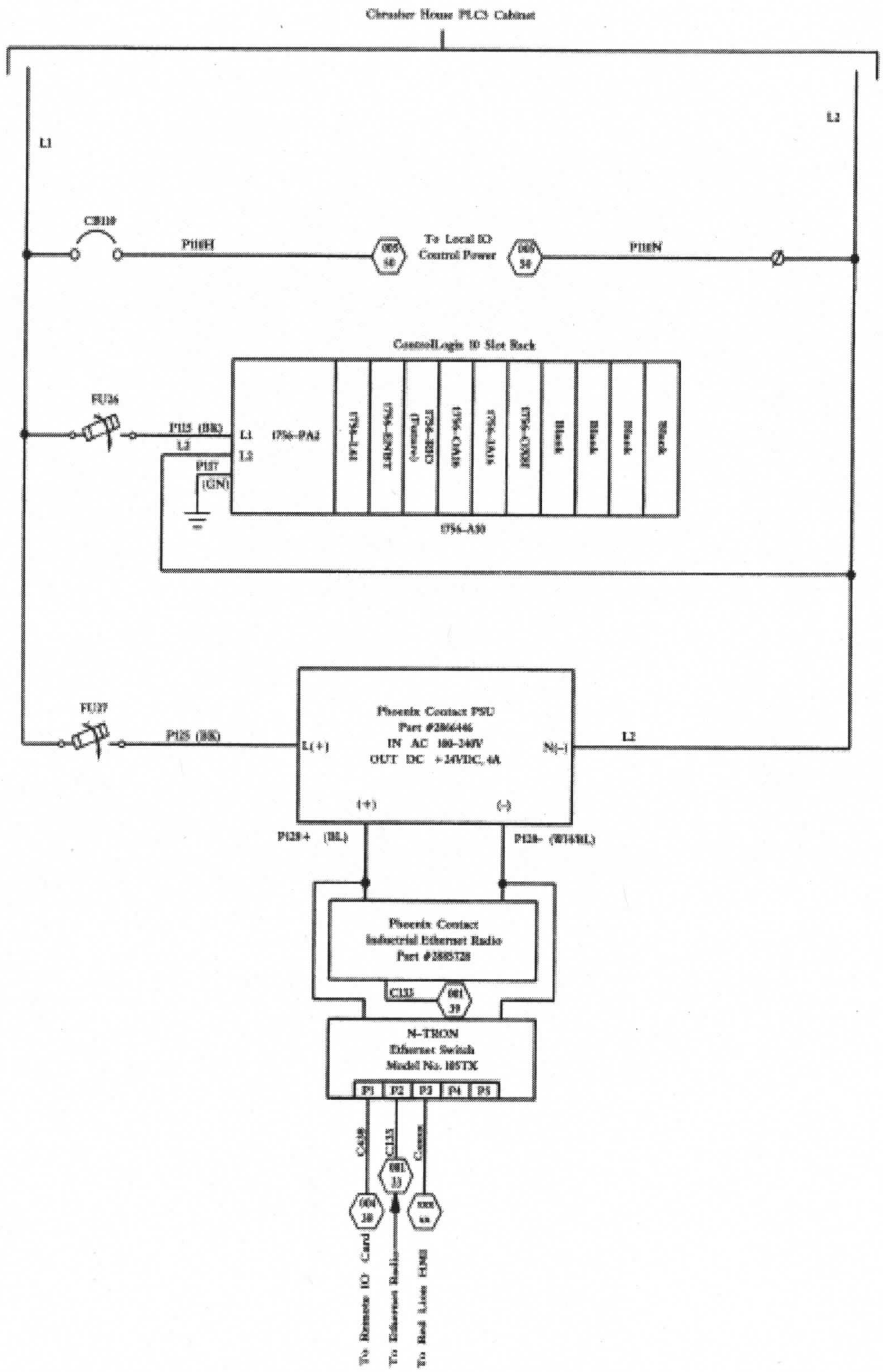

Figure 16. Laser Control System Master Rack Wiring Diagram

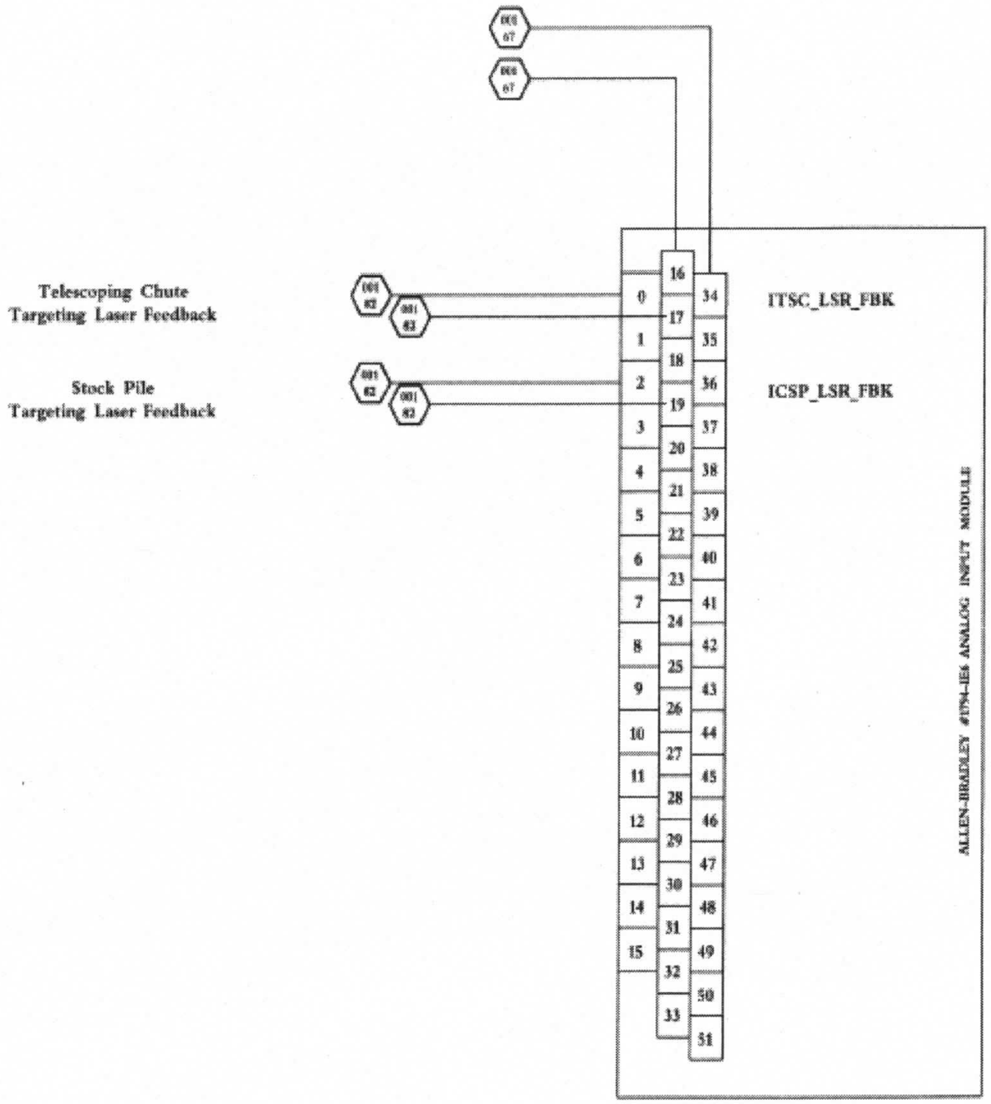

Figure 17. Laser Analog Feedback Entry Point

3.4 The Laser Control System Software Routines

Since installation of lasers on a telescoping chute is a novel application for this power plant, development of the control software was the most challenging aspect of the project. Design of the control software included several challenges. The challenges were that system could not override any of the existing relay logic which included upward movements, fully extended position, and fully retracted position.

In order to automate the downward movement of the chute the distance between the telescoping chute and the stockpile has to be determined. The lasers provide this information. Shown in Figure 18 is an overall block diagram of the control logic. The system is a close-loop proportional to the difference between the stockpile height and the telescoping chute downward position.

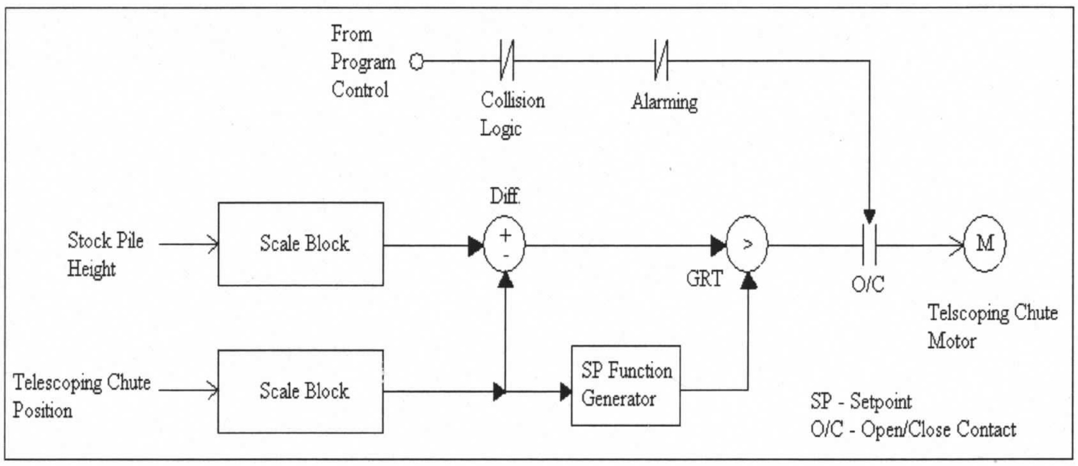

Figure 18. Control Logic Block Diagram

3.4.1 The Scale Block

The scale block algorithm calculates the linear slope of the inputs and outputs. The two tags shown in Figure 19, ITSC_LSR_FBK and ICSP_LSR_FBK, are assigned to the analog input card. The analog card makes an A/D conversion and converts the signals from 4-20mA to a 15-bit integer. The integer is then scaled from 0 – 32767 to a value distance of 1-20 meters (3-75 feet). The 1m (3ft) offset is because the lasers have a 1m (3ft) guard zone in which there can be no objects, which is useful to sense when the lasers are dirty. If the lasers are dirty, a false reading can be returned to the control system, possibly causing false moves. The governing equation and sample calculations are shown in equation 3.1 below:

$$Yout = \frac{(Y_{al} - Y_{\min})(H_{\max} - H_{\min})}{(Y_{\max} - Y_{\min})} + (H_{\min}) \tag{3.1}$$

where:

Y_{out} = output that represents scaled value of the analog input (feet).
Y_{al} = the analog signal input.
Y_{min} =the minimum value attainable by the input to the instruction.
Y_{max} = the maximum value attainable by the input to the instruction.
H_{max} = the scaled value of the input corresponding to Y_{max} (ft).
H_{min} = the scaled value of the input corresponding to Y_{min} (ft).

Sample Calculations:

$$Y_{out} = \frac{(24023-0)(75-3)}{(32767-0)} + 3 = 55.768\,ft \quad (16.99m)$$

$$Y_{out} = \frac{(15890-0)(75-3)}{(32767-0)} + 3 = 37.915\,ft \quad (11.56m)$$

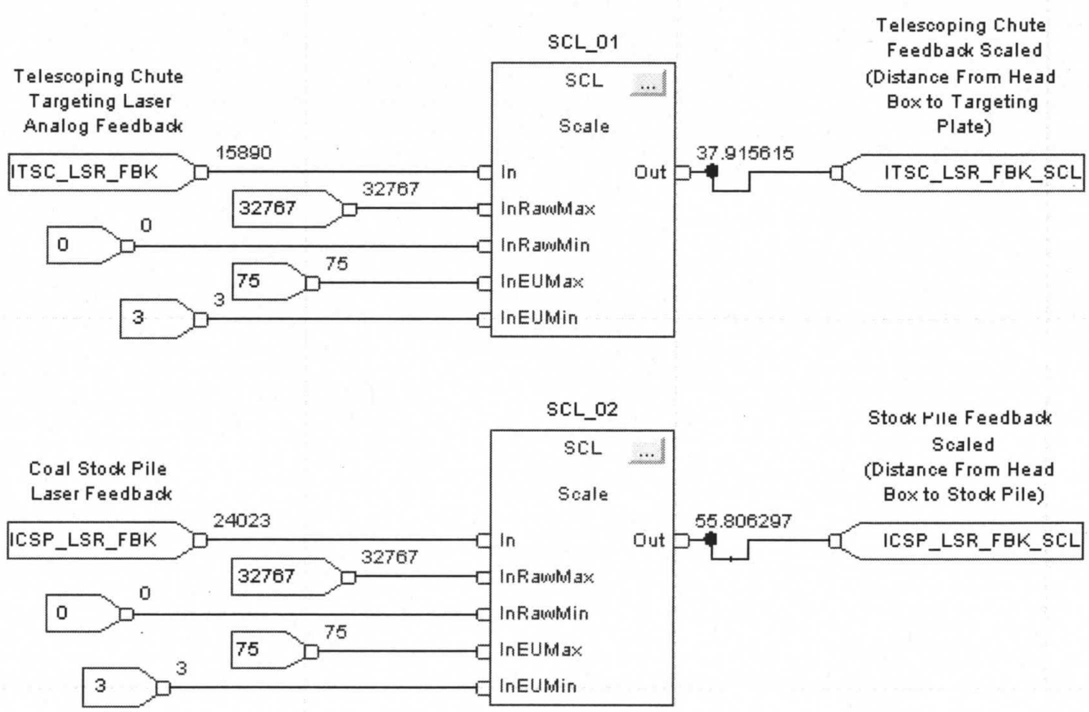

Figure 19. Laser 4-20mA Feedback Inputs

3.4.2 The Difference Block

Shown in Figure 20 is the subtraction block which subtracts the scaled feedback of the chute position from the scaled feedback of the stockpile height. This value is the input into alarm block noting that this value is the difference between the stockpile and the telescoping chute position. It should noted, that the value is equal to 5.400m (17.717 ft).

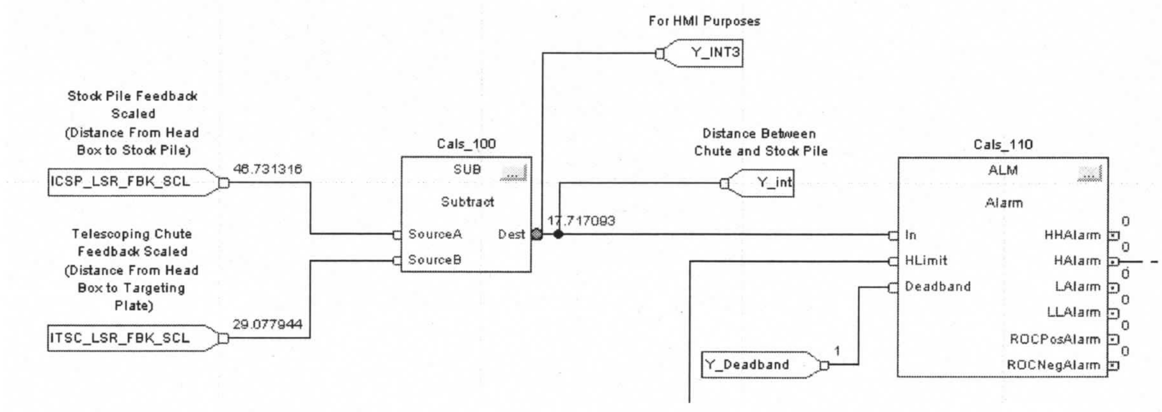

Figure 20. Difference Block

3.4.3 The Alarm Block

The alarm block is the greater than (GRT) function of the block diagram shown in Figure 18. The alarm block will make a comparison of the input to the setpoint in *HLimit* along with the Deadband setpoints, to either turn the output on or leave in the off state. If the output state of the alarm block is on and other downstream conditions (collision logic, alarms) are satisfied then the chute will move downward. The alarm block algorithm used to determine when to move the telescoping chute downward is shown in Figure 21 [12].

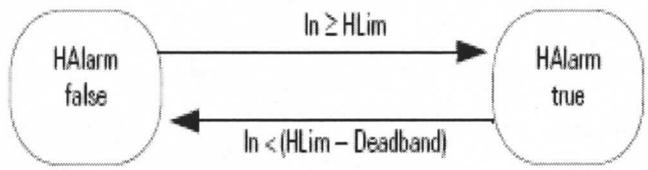

Figure 21. Alarm Block Algorithm

3.4.4 The SP Function Generator

Referencing Figure 18, the SP function generator block shown is the portion of the control logic that generates a setpoint for *HLimit* in the alarm control block. Shown in Figure 22 is the Function Generator used to create the setpoint for the alarm block. The function generator (FGEN) instruction converts an input value based on a piece-wise linear function [12].

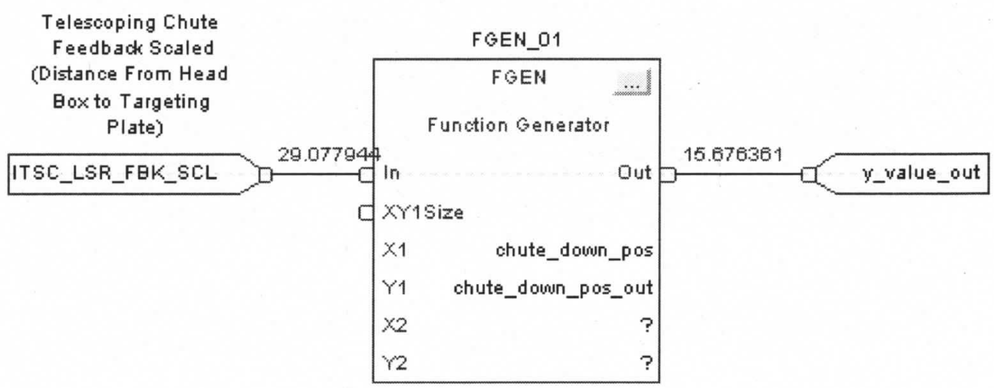

Figure 22. Function Generator

The value that is shown into the input of the function generator is the telescoping chute scaled position. This value is 8.86 m (29.078 ft) and was the measured position of the telescoping chute at the time of the observation. This function generator block has been configured with 15 points on the x and y axis and is listed in Table 1 below. The x-axis is the height profile of the chute and the y-axis is a user settable setpoint that corresponds to the position of the chute. The points are segmented into 0.9144 m (3 ft) divisions. The formula for the output tag *y_value_out* is listed below along with a sample calculation:

Table 1. Function Generator Point Table

n	x (ft)	x (m)	y (ft)	y (m)
0	7	2.13	9	2.74
1	10	3.05	9	2.74
2	13	3.96	9.5	2.90
3	16	4.88	10.2	3.11
4	19	5.79	10.7	3.26
5	22	6.71	11.2	3.41
6	25	7.62	12	3.66
7	28	8.53	15.5	4.72
8	31	9.45	16	4.88
9	34	10.36	17.5	5.33
10	37	11.28	19.9	6.07
11	40	12.19	20.9	6.37
12	43	13.11	21.9	6.68
13	46	14.02	22.3	6.80
14	49	14.94	22.9	6.98

$$F_{out} = \{\frac{[Xin - X(n)]}{[X(n+1) - X(n)]}[Y(n+1) - Y(n)]\} + Y(n) \tag{3.2}$$

where:

Fout = Output of the instruction [12].
Xin = The analog signal input to the instruction [12].
X(n) = *x*-axis array, Table 1 above. Combine with the *y*-axis array of Table 1 to define the points of the first piece-wise linear curve [12].
Y(n) = *y*-axis array, Table 1 above. Combine with the X-axis array, Table 1 to define the points of the first piece-wise linear curve [12].
n = *n* and *n*+1 are the indices of the points in Table 1 whose *x*-values bracket the value of *Xin.*

Example:

- $Xin = 29.077 ft$
- $n = 7$
- $n+1 = 8$
- $X(7) = 28.0 ft$
- $X(8) = 31.0 ft$
- $Y(7) = 15.5 ft$
- $Y(8) = 16 ft$

$$Fout = \{\frac{(29.077 - 28.0)}{(31.0 - 28)}(16 - 15.5)\} + 15.5 = 15.678\,ft\ (4.78m)$$

It should be noted that the setpoint is equal to 4.78m (15.7 ft). The difference between the stockpile and the telescoping chute is equal to 5.40m (17.7 ft). The difference is greater than the setpoint, therefore, the telescoping chute should be moving downward. However, the output from the alarm block (*HAlarm*) shown in Figure 20 is at a low or zero. The telescoping chute is not moving downward. This is due to a collision event between the stockpile and telescoping chute.

3.4.5 The Collision Logic

A collision occurs when the telescoping chute moves downward and the contact probes mounted on the end of the chute come in contact with the stockpile. Logic has been designed to detect this event and stall any further downward motion. Upward moves always have priority over downward moves. This is to prevent the telescoping chute from overdriving into the stockpile. The logic has been designed as shown in Figure 23.

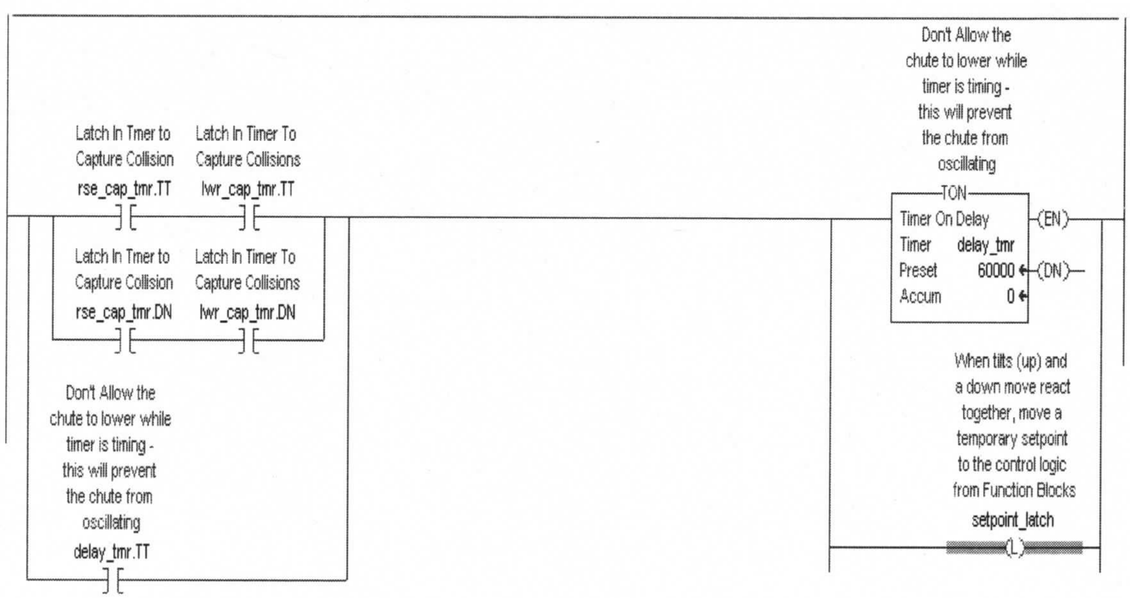

Figure 23. Collision Logic

Collision detection is a vital part of the performance of this system. The logic has two primary purposes, the first being to stall the downward movements and the second to prevent oscillations occurring in the telescoping chute motor starter circuits. The logic is designed to capture when the chute has a command to move down (*lwr_cap_tmr.TT*) and to move up (*rse_cap_tmr.TT*) simultaneously. This starts a one-minute timer called *delay_tmr* and will prevent the system from making any downward movements. At the same time, *setpoint_latch* has been set and has started another timer that will stall for additional five minutes. This additional time is to allow the stockpile to decay to where auto moves can be made. This logic was designed as a fail-safe mechanism to prevent excess collisions and oscillations and enhance the performance and reliability of the telescoping chute.

3.4.6 System Alarms

A number of alarms were designed and implemented preventing risk to personnel and equipment damage, and shut down the system if necessary. The alarms that have been added fall into two categories: disabling and warning alarms. The warning alarms are classified either as minor, major or warnings. Minor alarms will automatically reset once the issue has been cleared. Additionally, minor alarms cause a one minute stall to prevent damaging oscillations. Major alarms, of which there are only two, require user intervention to restart the system. Warning alarms indicate status of the control system and lasers. The alarms are listed below along with a short explanation:

- Remote IO Fault (Minor) – an issue has occurred with slave rack IO.
- Remote AC Power (Minor) – AC power has been lost at the slave rack.
- Emergency Stop (Minor) – emergency stop has been pressed at the operator interface.

- Telescoping Chute Laser Fault (Minor) – diagnostic issues have been detected with the telescoping chute laser.
- Stockpile Laser Fault (Minor) - diagnostic issues have been detected with the telescoping chute laser.
- Wireless Communications Fault (Minor) – the wireless communications has faulted
- Laser System Fault (Minor) – stockpile and telescoping chute are within critical distance of each other
- Telescoping chute Laser High Deviation – the telescoping chute has high variability, which is erratic feedback usually caused by high dust.
- Stockpile Laser High Deviation (Minor) – the stockpile laser has high variability.
- Tilt Timer Exceeded (Major) – fail-safe alarm, shut down #1conveyor and train hopper systems.
- Retract Overtravel (Major) – the telescoping chute has traveled past the minimum laser limits, shut down train hopper systems.
- Chute Approaching Retract Position (Warning) – warning to indicate that telescoping chute is approaching retracted position.
- Chute Approaching Extended Position (Warning) – warning to indicate that the chute is approaching extended position.
- Chute Fully Extended (Warning) – the telescoping chute has traveled past the laser setpoint for extended position.

3.4.7 The Output Control (O/C)

Finally, the output of the alarm block in Figure 20, *lwr_init*, is the input into a series of emergency stop logic elements which leads to another block (see Appendix C for complete listing) whose output is LWR_MODE_ENG. This output is then inserted into an output rung, shown in Figure 24, which is the telescoping chute downward movement motor starter circuit. As stated earlier, if the difference of the telescoping chute is greater than the value of *HLimit*, the chute engages downward. This assumes no collisions have occurred, no major or minor alarms are active, and the telescoping chute is within travel limits.

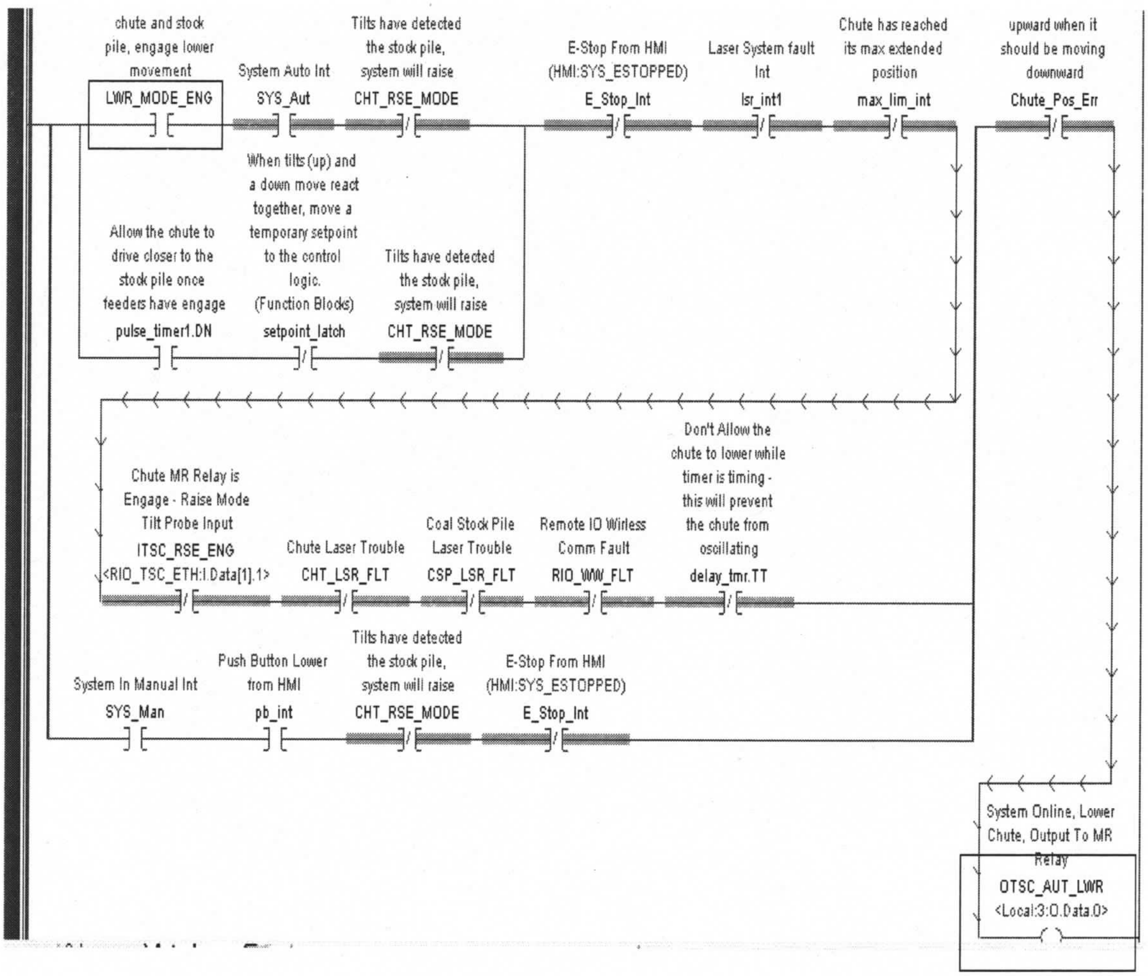

Figure 24. Downward Movement Logic for the Telescoping Chute

Chapter 4

Experimental Results

Range sensor analysis involved the comparison of sensor data with measured data for each system. As stated previously, range sensors tested were ultrasonics systems, radar guided systems and laser systems. The three systems measure the height of a coal stockpile either in coal silos (Figure 2), open air (Figure 4) or the train receiving hopper (Figure 8). All three systems installed are in a hostile operating environment, exposed to dust, weather and high heat. The range sensor feed back signals were compared to tape measure results. The tape measure results are considered standard or known-correct values to which the electronic measurements systems were made.

4.1 Ultrasonic System Results

The ultrasonic height data and tape-measure height data are shown in Figure 26. There are 26 silos in which one measurement was made for each silo. Shown in Figure 25 is the tape measure, with a weight attached to the end, which was lowered into each silo until it made contact with the coal. The tape is considered the standard to which all measurements are compared and calibrated against. The tape measure height was subtracted from the total height of the silo. Next, the height feedback was subtracted from the measured feedback and an error with respect to the total height of the silo was calculated. Example calculations of silo 1B are shown below:

Where:

1B Silo Total Height = 9.75m
1B Tape Measure = 6.60m
1B Measured Height = 9.75m – 6.60m = 3.15m
1B Actual Height = 3.41m
1B Err = ((3.15 – 3.41)/9.75) × 100 = -2.7%

Additionally, units 1 and 2 (silos1A, 1B, 1C, 2A, 2B...etc) the sensing range inside the silos is 9.75m (32.0 ft) and the total height of the silos being 11.3m (37.0 ft). On unit 3 (silos 3A, 3B, ... etc) the sensing range inside the silo is 15.2m (50.0 ft) with the total height being 16.8m (55.0 ft). The ultrasonic systems are aimed downward toward the top part of the conical section of the silo. It should be noted that the conical section of the silos or hoppers is the bottom part of those storage systems (see Figure 2 for an illustration). This is due to false reflections begin to occur within the conical height of the silo. It is very important to maintain the coal level above the conical section due to the pressurized feeder system below the silo. If a hole in the coal or a low level occurs, then the air system below the silo could blow hot air into the top of the silo which would put personnel at risk if they are present in the house above the silo.

Figure 25. Tape Measure

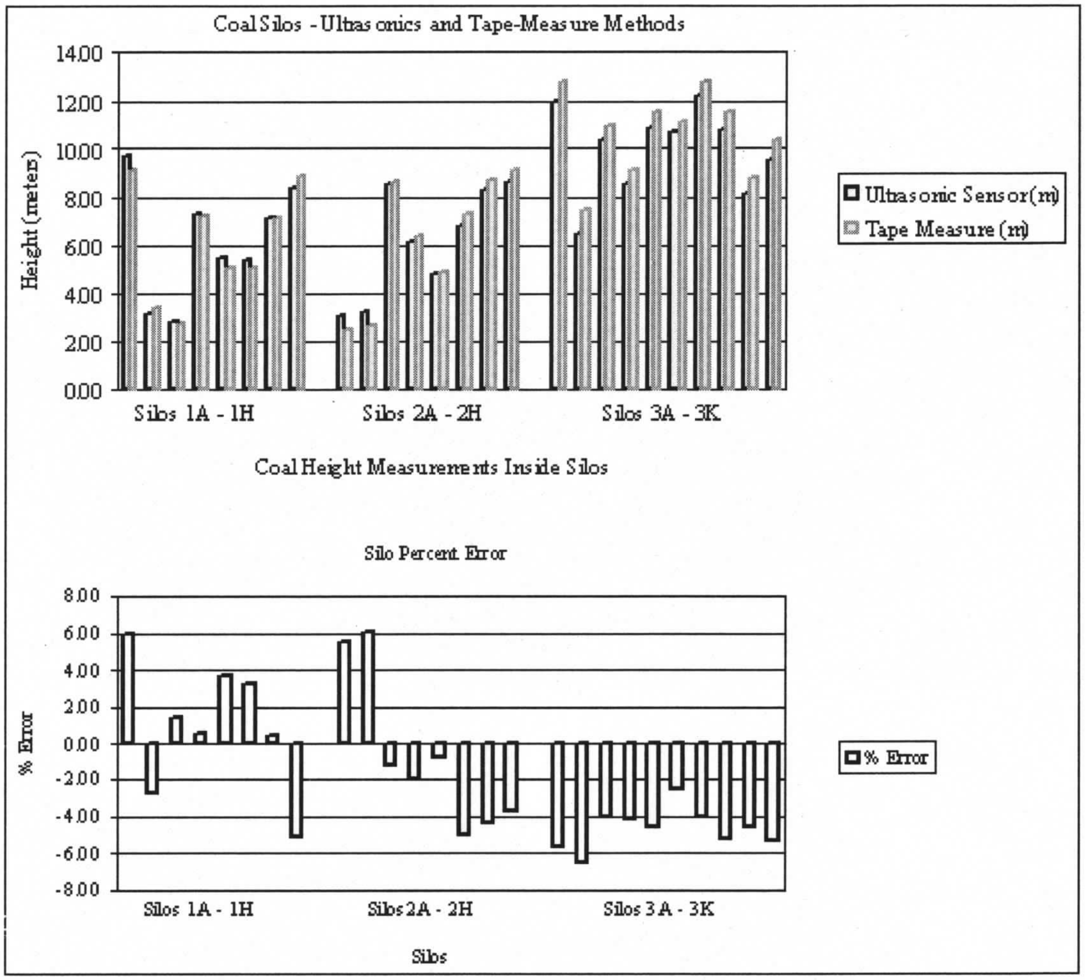

Figure 26. Ultrasonic – Coal Height Performance

4.2 Radar System Results

In Figure 27 are the results of four radar level sensors mounted at the top of the train receiving hoppers. The chart is oriented from left to right with one data point from each sensor. Again, a tape measure was dropped into the top of the hoppers and as before the values were placed in a spreadsheet and error calculations were made. The height of the hopper is 11.6m (38 ft) from the radar position to the bottom of the hopper. The radar probes are mounted at the top of the hopper and oriented vertically downward. The total downward sensing distance of the radar system is 11.6m (38 ft). These radar systems have been in operation for about one year

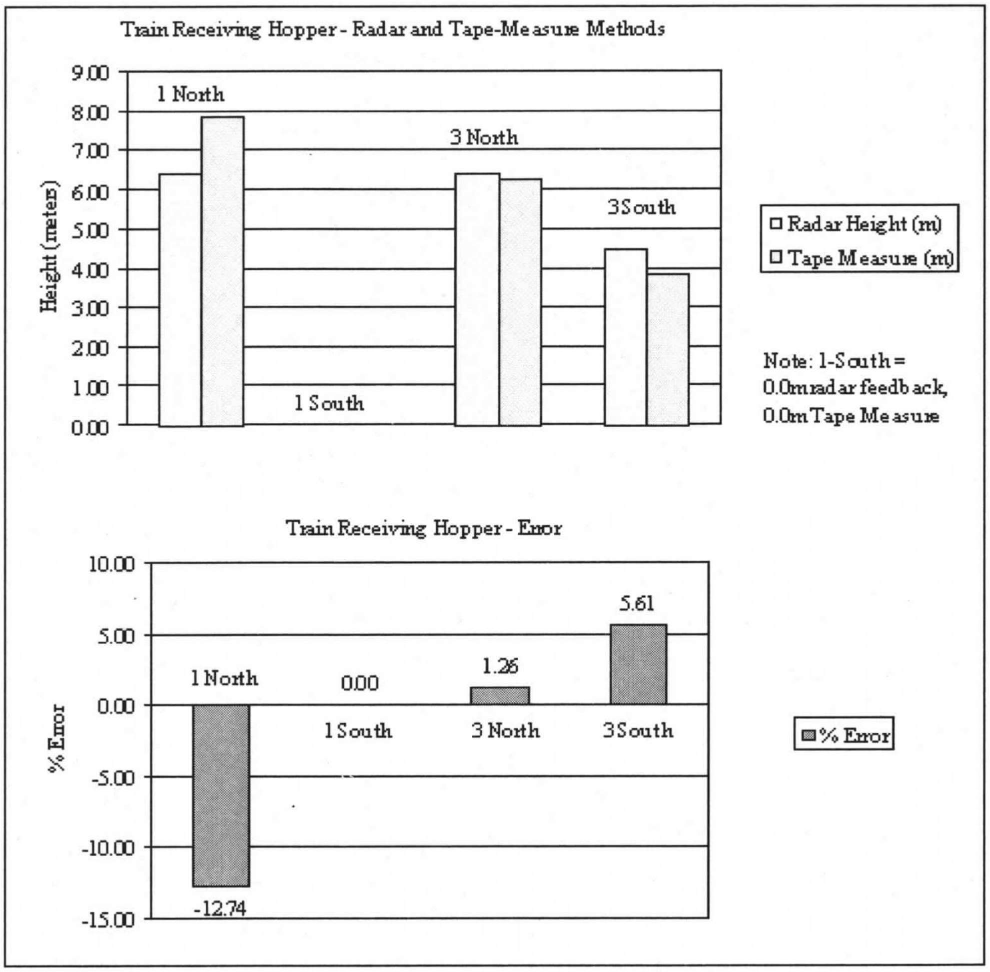

Figure 27. Radar – Coal Height Performance

Note:

1) The height of coal measured in receiving hopper 1-South were 0.0m as measured both by radar and the tape measure.

4.3 Laser System Results

Illustrated in Figure 28 are the laser positions relative to their targets. One laser is sensing the stockpile height and the other laser is sensing the position of the telescoping chute from a targeting plate. These signals are then fed back into the control system creating a setpoint, and then the chute is moved to the range of the setpoint position. It should be noted, the control system calculates the telescoping chute downward position based upon the distance from the laser to the telescoping chute. It should be further noted, the control system calculates the distance from the laser to the top of the stockpile. The height of the stockpile is calculated and displayed by subtracting the stockpile laser feedback from 20m (67 ft). The height of the stockpile, relative to the ground is not used in the movement profile of the telescoping chute. The distance between the telescoping chute and the top of the stockpile (Figure 28 – "y") is the measurement that is desired. The downward chute position is also displayed but it is absolute to the end position of the telescoping chute and the laser. The telescoping chute position in relation to the ground is not important for program calculations. In Figure 29 are the results from the laser system and each laser has two data points. From left to right, points 1 and 3 represent telescoping chute laser data at different heights and points 3 and 4 are the stockpile laser data taken at different heights.

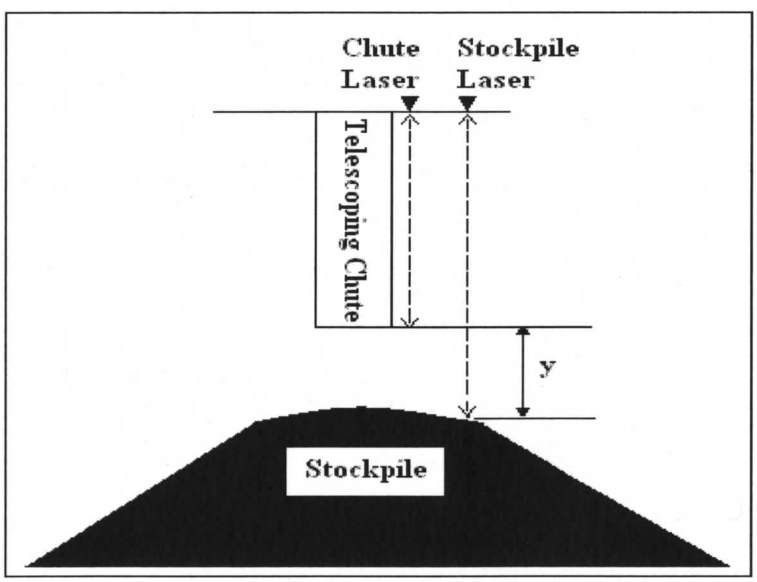

Figure 28. Laser Position Illustration

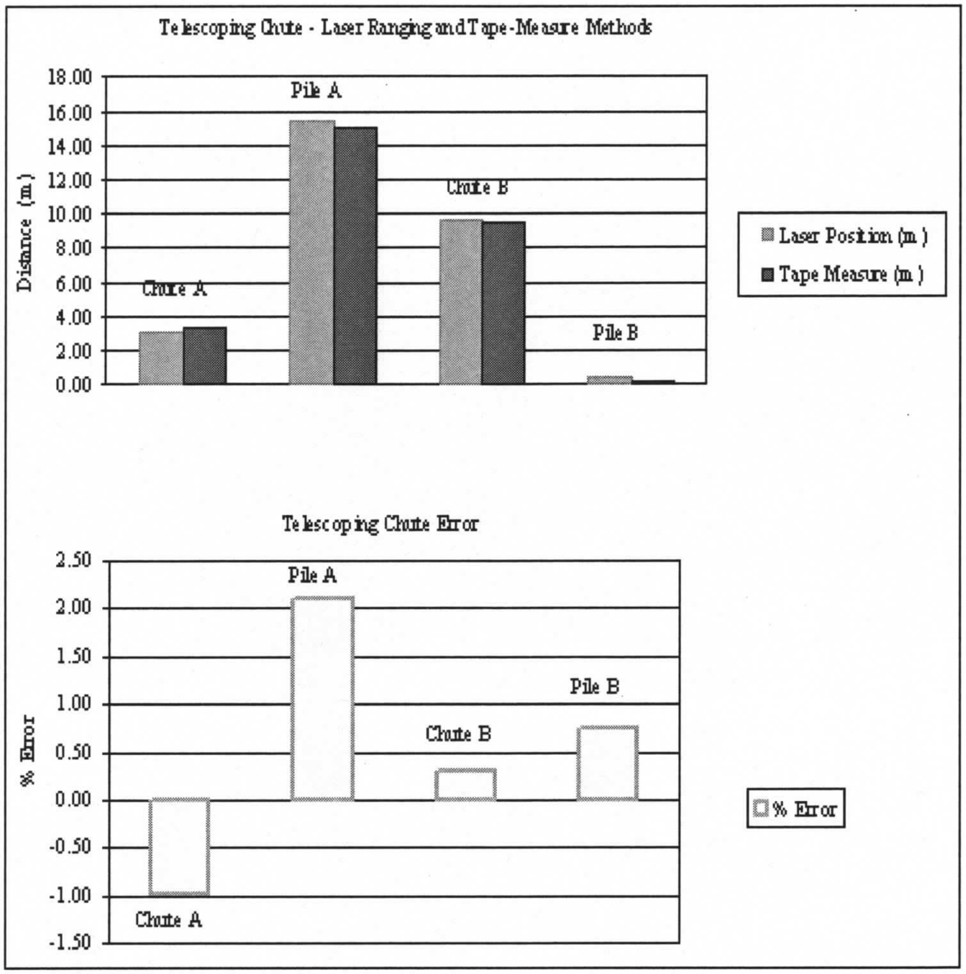

Figure 29. Laser Targeting Performance

Chapter 5

Conclusions

In this thesis research, a continuous position control system for a telescoping coal chute was developed and implemented. As part of this investigation, three types of coal-level sensors were analyzed: ultrasonics, radar guided, and laser systems. A detailed analysis of each sensor modality is provided, along with some conclusions regarding their performance.

5.1 Laser Implementation Enhancements

The laser system has been in operation since June 1, 2009. The system is a first of a kind for this coal-fired power plant and it has performed very well integrated with existing operations. One of the major issues faced was that the coal stockpile does not decay symmetrically. One side of the stockpile will decay faster than the other side and there is only one laser sensing the stockpile. In order to combat this issue, a heuristic set - point lookup table was developed for the decay of the stockpile. The setpoint (*HLimit*) is dynamically changed based upon the chute position. Collision logic prevents the controller from sending commands to move down and up at the same time. Shown in Figure 30 is plot of the movement history of the telescoping chute under the new control system in coordination with the set-point generator. This plot is a typical profile for the telescoping chute. The chute moves into position relative to the stockpile (setpoint management) and as the stock pile height increases, the chute will move upward until it reaches the fully retracted position. The system will not allow upstream feeder systems to start unless the chute is in the proper starting position as specified by the control system. It should be noted that when the chute is moving downward, it is moving away from the chute laser causing the distance feed back to increase. Additionally, when the chute is making moves upward the laser distance feed back is decreasing. The stockpile laser feed back displayed in Figure 30 is measured from the laser to the height of the stockpile. The total height of the telescoping chute (Figure 4) is known and the control system calculates the height of the stock pile for display purposes (HMI). However, the height of the stockpile is not important for control purposes, since the distance between the stock pile and the chute is the data that is being compared for setpoint calculations.

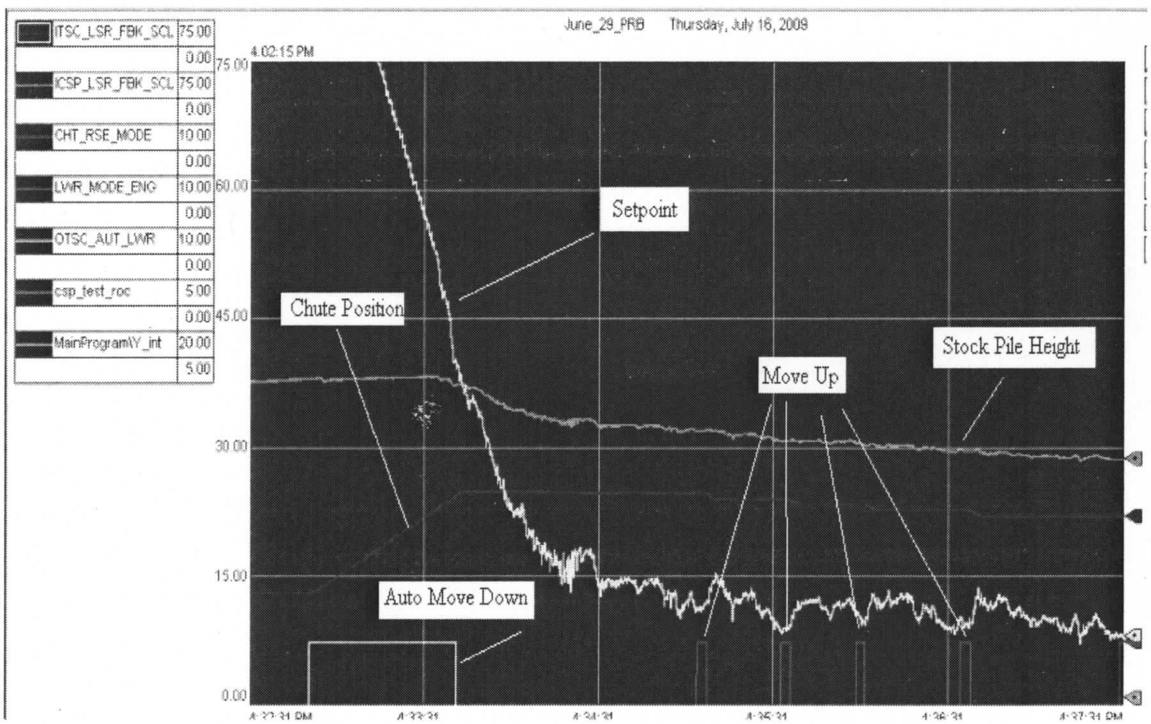

Figure 30. Telescoping Chute Movement Profile Under Laser Guidance

5.2 Ultrasonic Systems

In Figures 26, 27, and 29 are the actual level measurements errors for of the three sensors. Analyzing data from the ultrasonic systems, it can be observed that the measurement error starts to grow as the coal approaches high or empty levels. This was evident in almost all of the silos except for silo 1C in which the error was only 1.4%.

These systems will measure actual coal height until the coal height has increased above 90% full or until the height has dropped below 30% full. The operational experience of the ultrasonic systems should be capable of accurate heights to within ± 1 meter. This will maintain sufficient coal heights which will prevent damaging events (blow-backs) from occurring. Additionally, it should be noted that the level feedback from operational experience starts to decay when the level drops below 50%. This is because the coal pile inside the silo starts to invert as the coal is being pulled from the bottom-center of the silo. In other words, the angle of repose starts to invert. The ultrasonic system is mounted on one side of the silo and it is aimed directly downward toward the outer edge of the coal pile.

5.3 Radar Systems

Analyzing data from the four radar probes, it was observed that they seem to exhibit behavior similar to ultrasonic ranging, meaning that error grows when the coal is at its maximum and minimum heights. This is evident with 1-North, in which there is a 1.46m (4.89 ft) difference in the sensor feedback level to level measured with the tape measure. Similarly, the level ranging for 3-South is in the middle of the span and has a 0.66m (2.17 ft) difference in sensor feedback versus measured level. As illustrated in Figure 8, the radars are mounted on top of the train receiving hoppers and aimed vertically to the bottom of the hopper. It should be noted that the radar is in the most hostile environment of the three sensors and this must be strongly considered for this comparison. The dust suppression systems constantly treat the coal with chemicals which can cause the coal dust to clump and adhere to the feed horns of the radar rangefinders. This constant exposure to a hostile environment adds difficulties to the successful employment of the radar sensors. The ultrasonic and laser systems also operate in harsh environments, but they are not as extreme as the environment of the radar sensors.

5.4 Laser Systems

The lasers are mounted at the same elevation with one aimed at a target on the telescoping chute and the second aimed downward toward the coal stockpile. There were two samples taken, one when the chute was fully retracted (stockpile high) and one when the chute was fully extended (stockpile low) under the setpoint management system of the program. In this system, the stockpile does not decay in a symmetric shape. The stockpile may or may not have holes or bridging as it decays. This does not occur for each extension of the chute. Due to non-symmetrical stockpile decay logical curves had to be developed in the controller to allow for variances in the stockpile and detect when the chute and stockpile collide. It should be noted the stockpile laser appears to be detecting its targets with no indication of issues.

5.5 Conclusions

Given their respective application and environmental differences, the laser ranging system outperformed the other two systems for level-detection accuracy. The major advantages of the laser system are that it can be aimed toward a small target and can accurately feed back data to the control system due to its narrow beam path. Geometry differences due to angle of repose therefore did not affect its performance in this application. A laser system could not be used to accurately estimate the overall stockpile geometry without a surface geometry model such as the angle of repose or one similar to the empirical model developed as a part of this research. However, the major disadvantage of the laser system is that there cannot be any obstructions in the line of sight of the laser. The ultrasonic and radar systems have built-in algorithms that can learn the sensing areas and ignore obstructions within line of sight. All three systems have built-in methods to adjust transmitted power to cope with varying path losses which, in this application, may arise from pluming dust interference. Another disadvantage of the laser system is cost. The lasers cost approximately twice as much as the other two systems. A large capital expense would be incurred if bulk replacement of ultrasonic or radar sensors with lasers is to be undertaken. Lastly, after careful observation and monitoring of all three systems, it is noted that the lasers demonstrate ability to more-accurately measure distances than ultrasonic and radar systems in this application.

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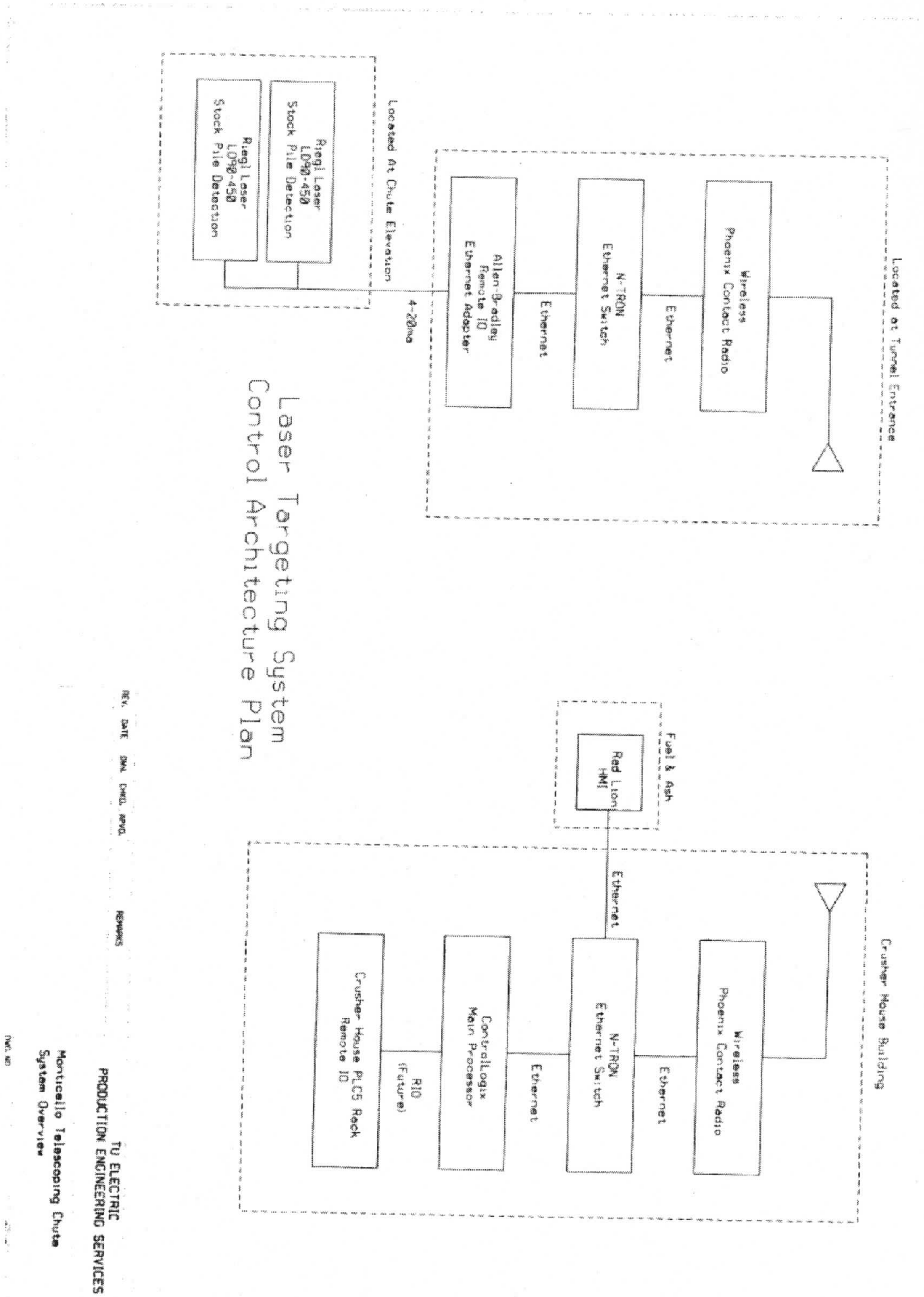
Appendix A – Laser System Electrical Diagrams

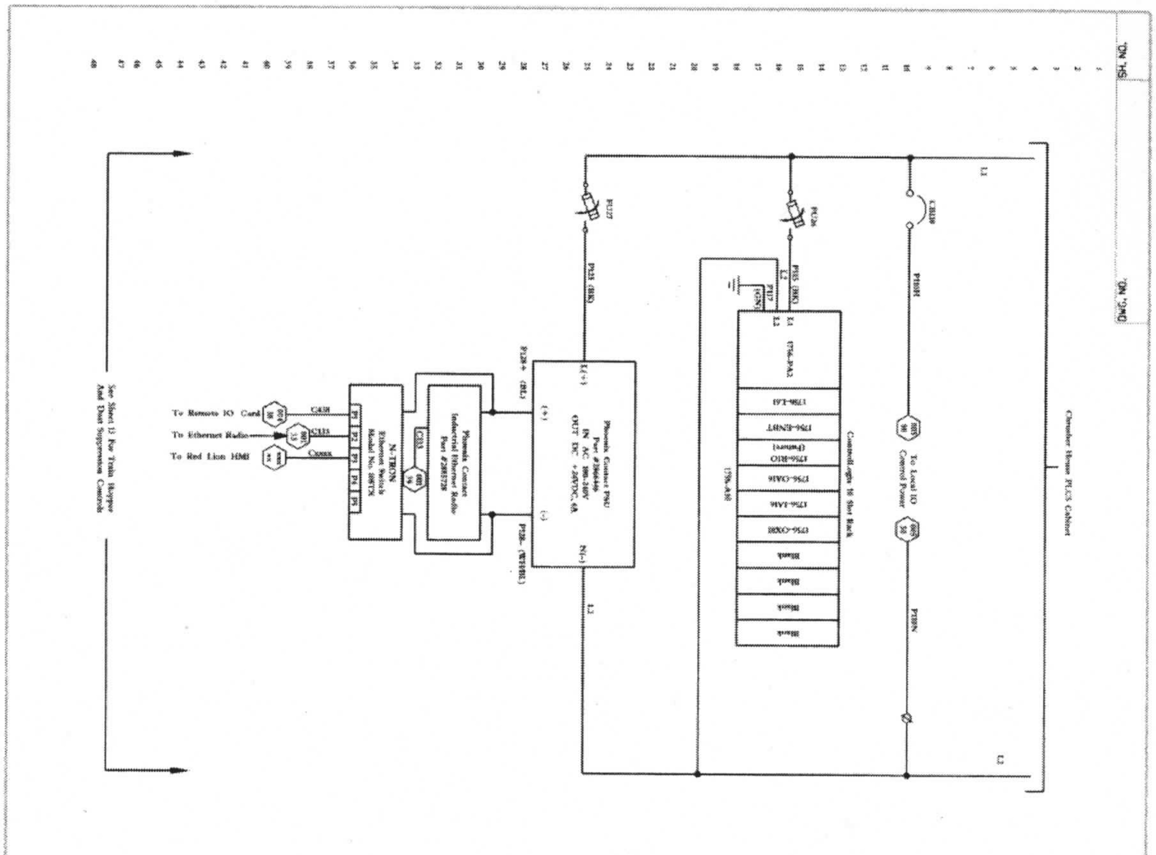
Attached below are the electrical diagrams, in a PDF format, to complete the laser project. The original prints are 11”x17” format.

Appendix A (Continued)



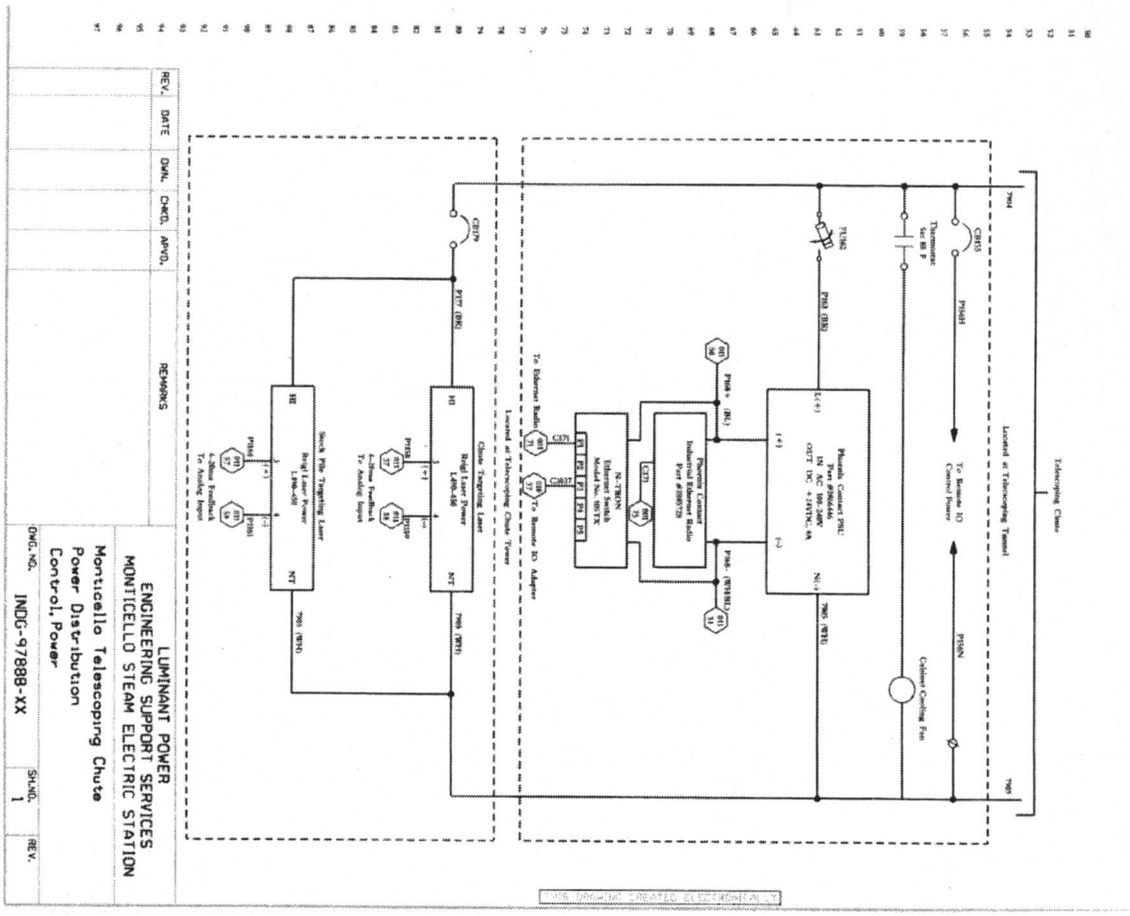
A - 1: Laser System Overview

Appendix A (Continued)



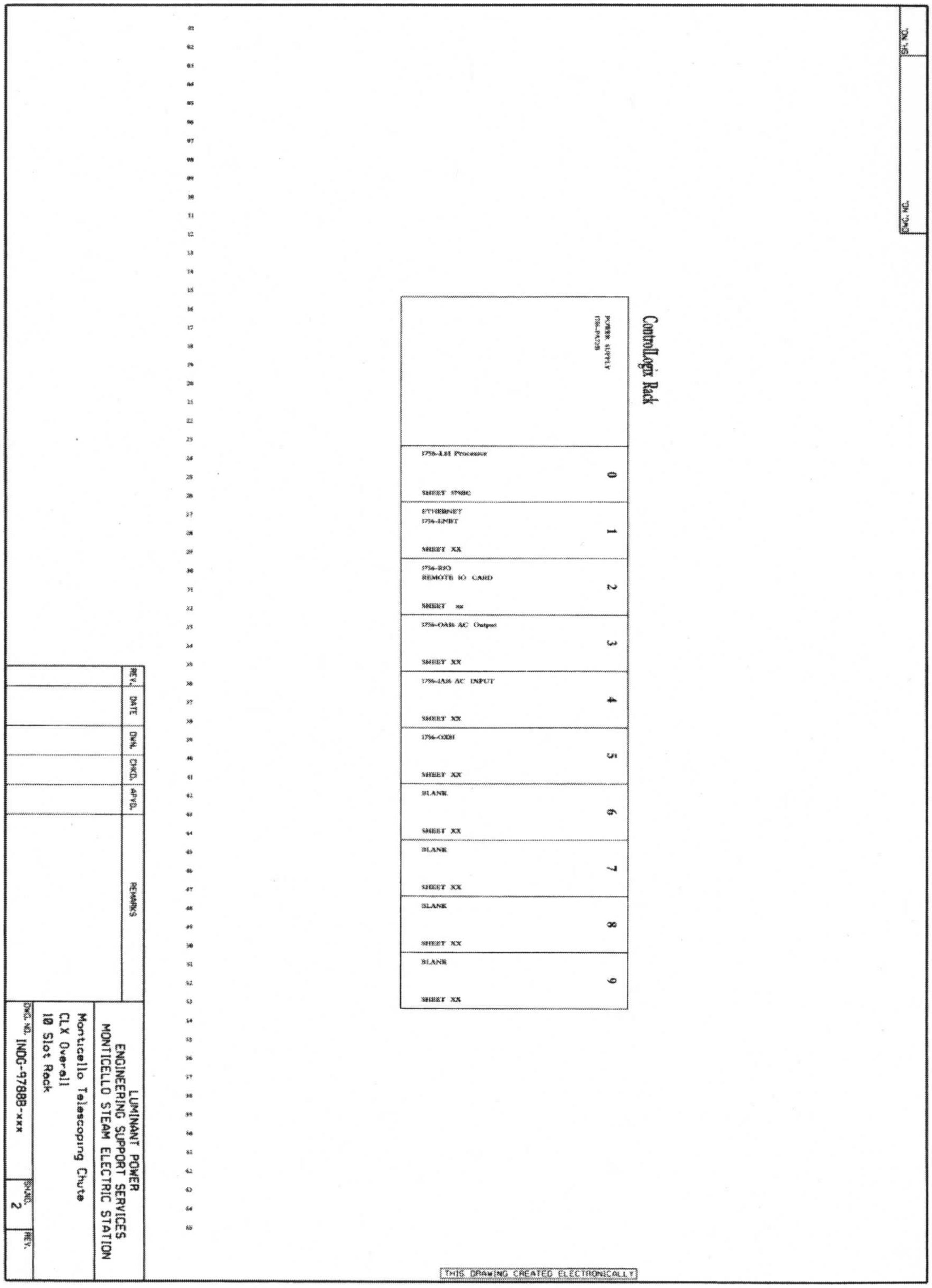
A - 2: Power Distribution A

Appendix A (Continued)



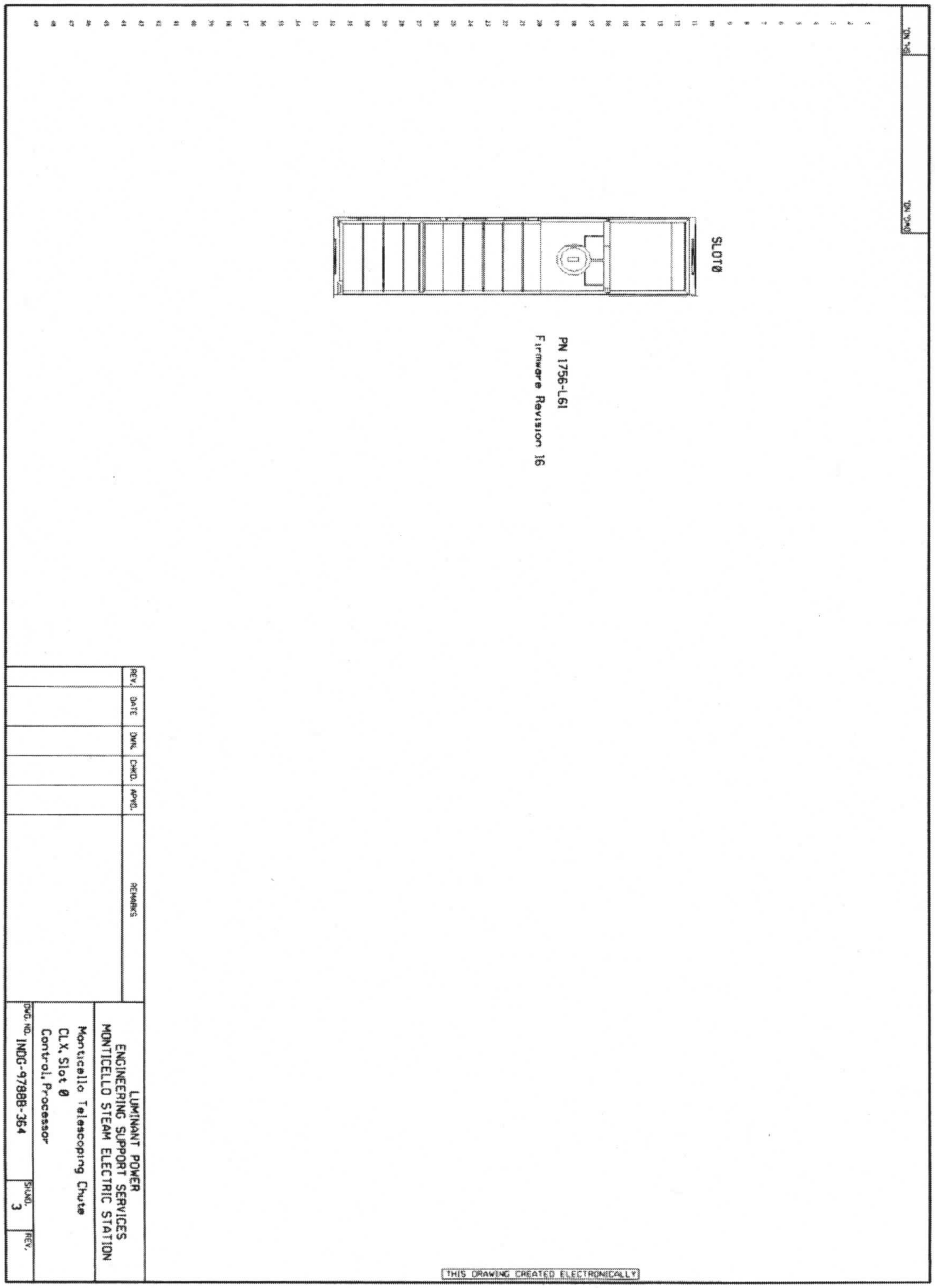
A - 3: Power Distribution B

Appendix A (Continued)



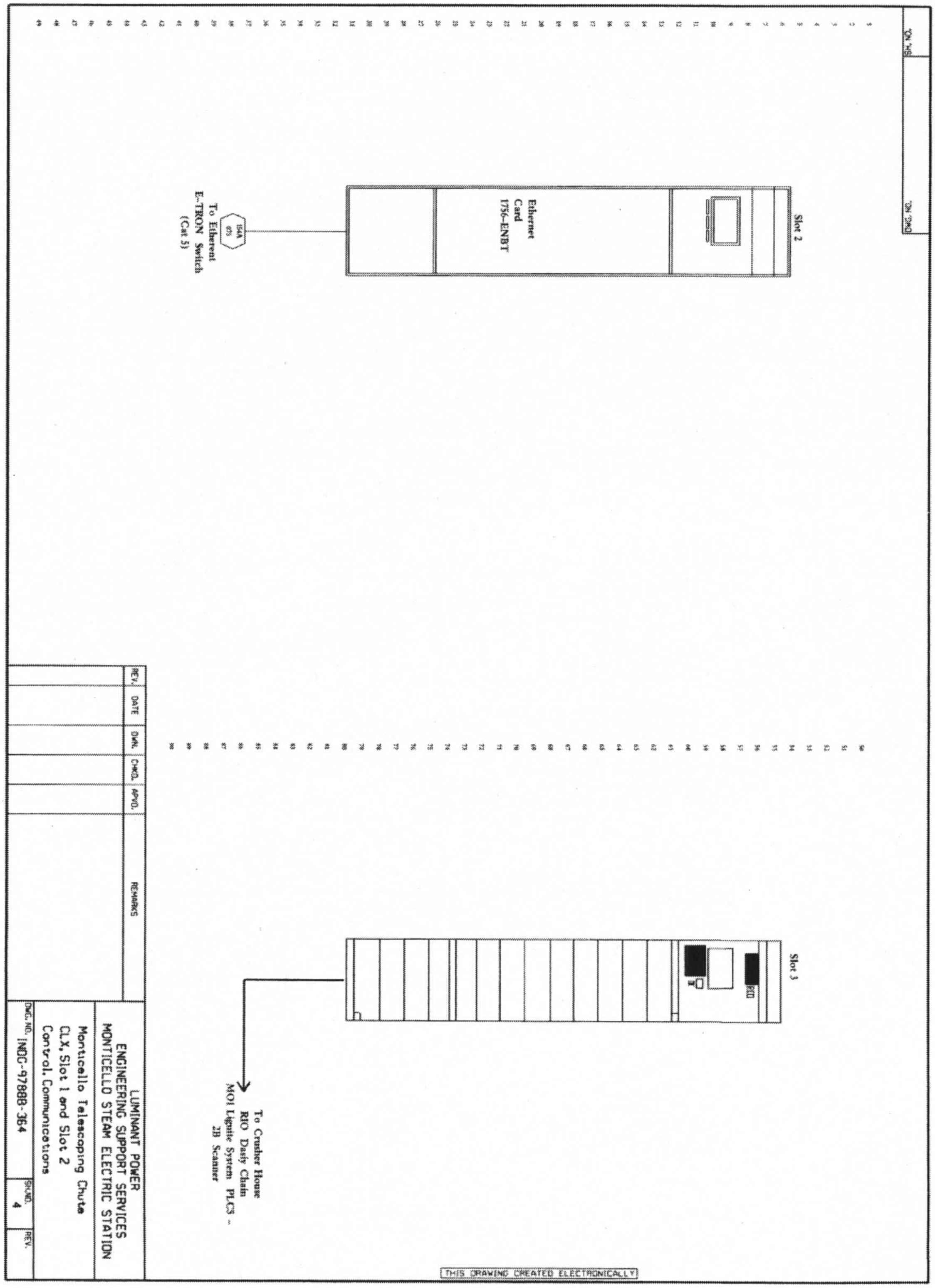
A - 4: ControlLogix Rack

Appendix A (Continued)



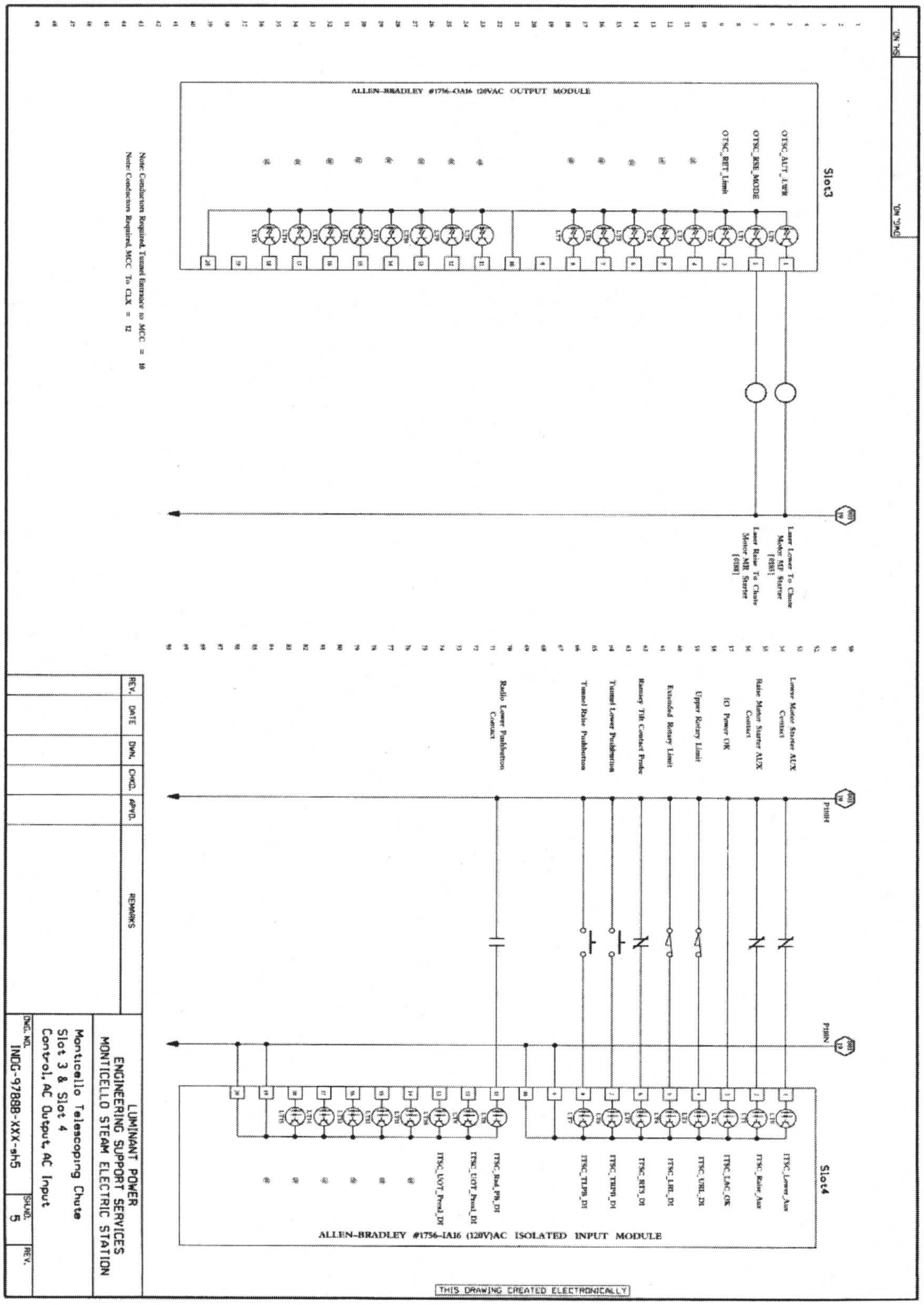
A - 5: ControlLogix Processor

Appendix A (Continued)



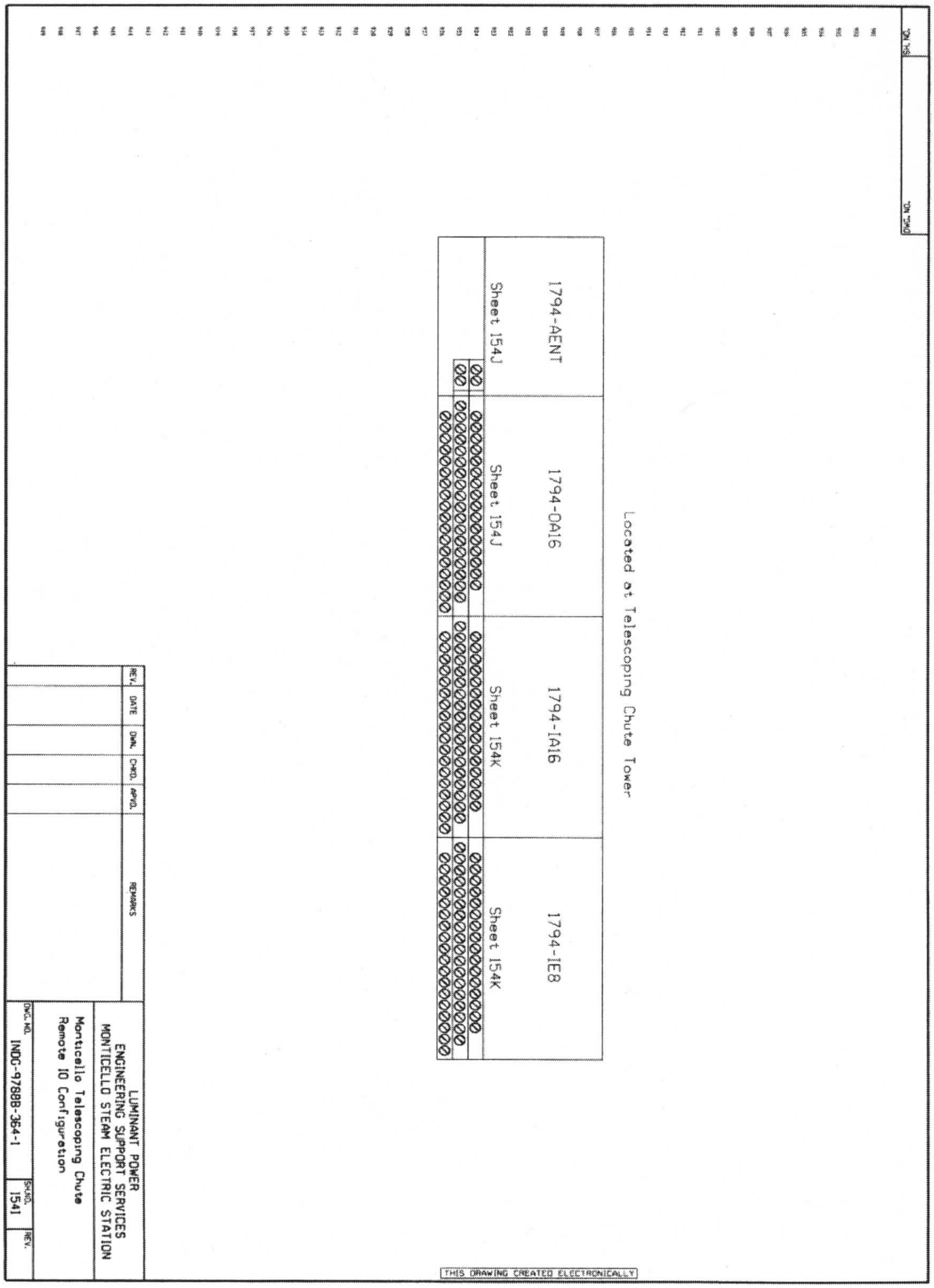
A - 6: Master Rack Communications

Appendix A (Continued)



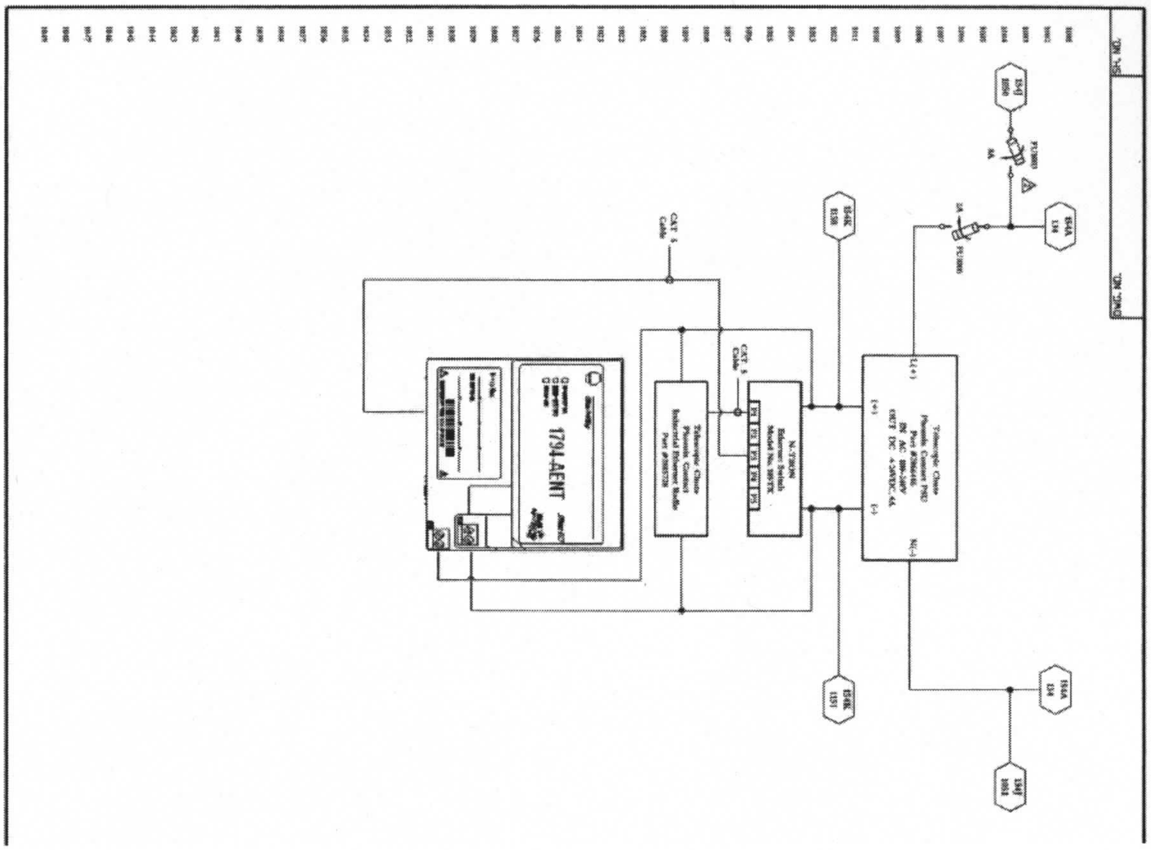
A - 7: Master Rack Local IO

Appendix A (Continued)



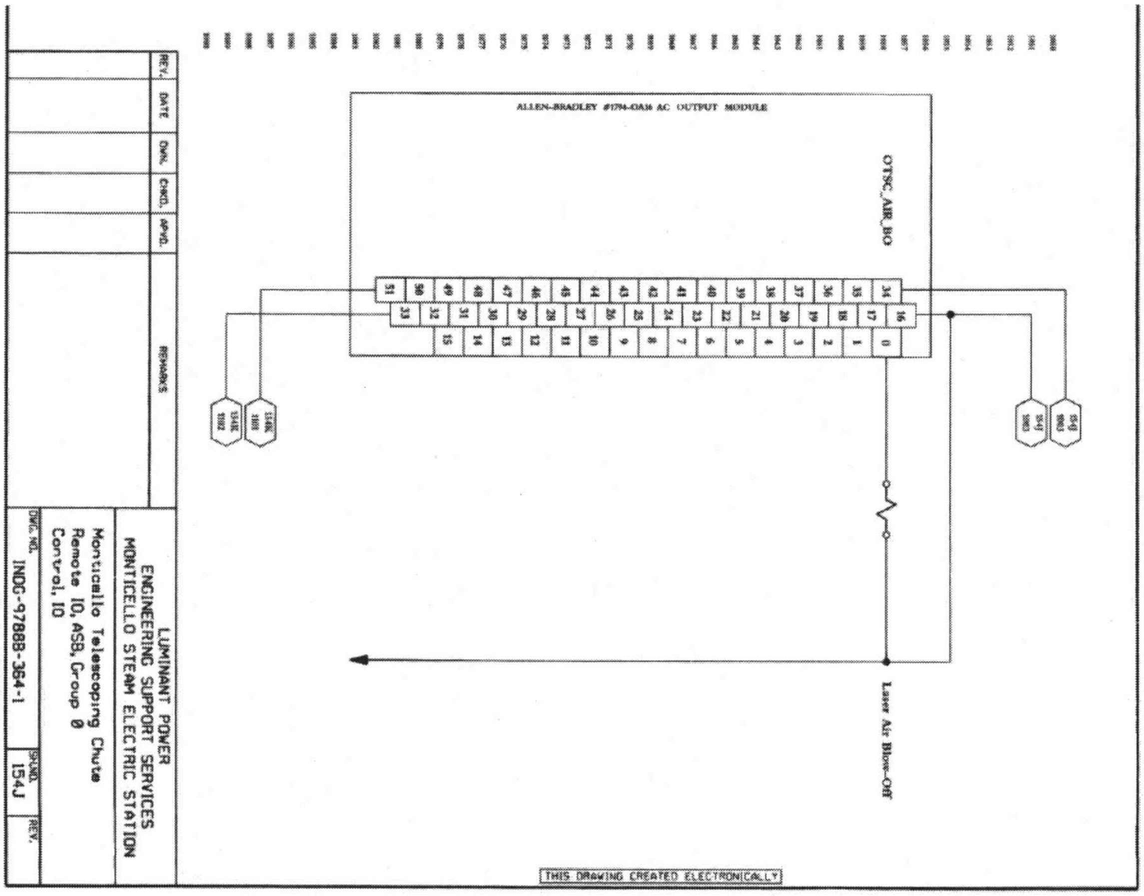
A - 8: Remote Slave Rack

Appendix A (Continued)



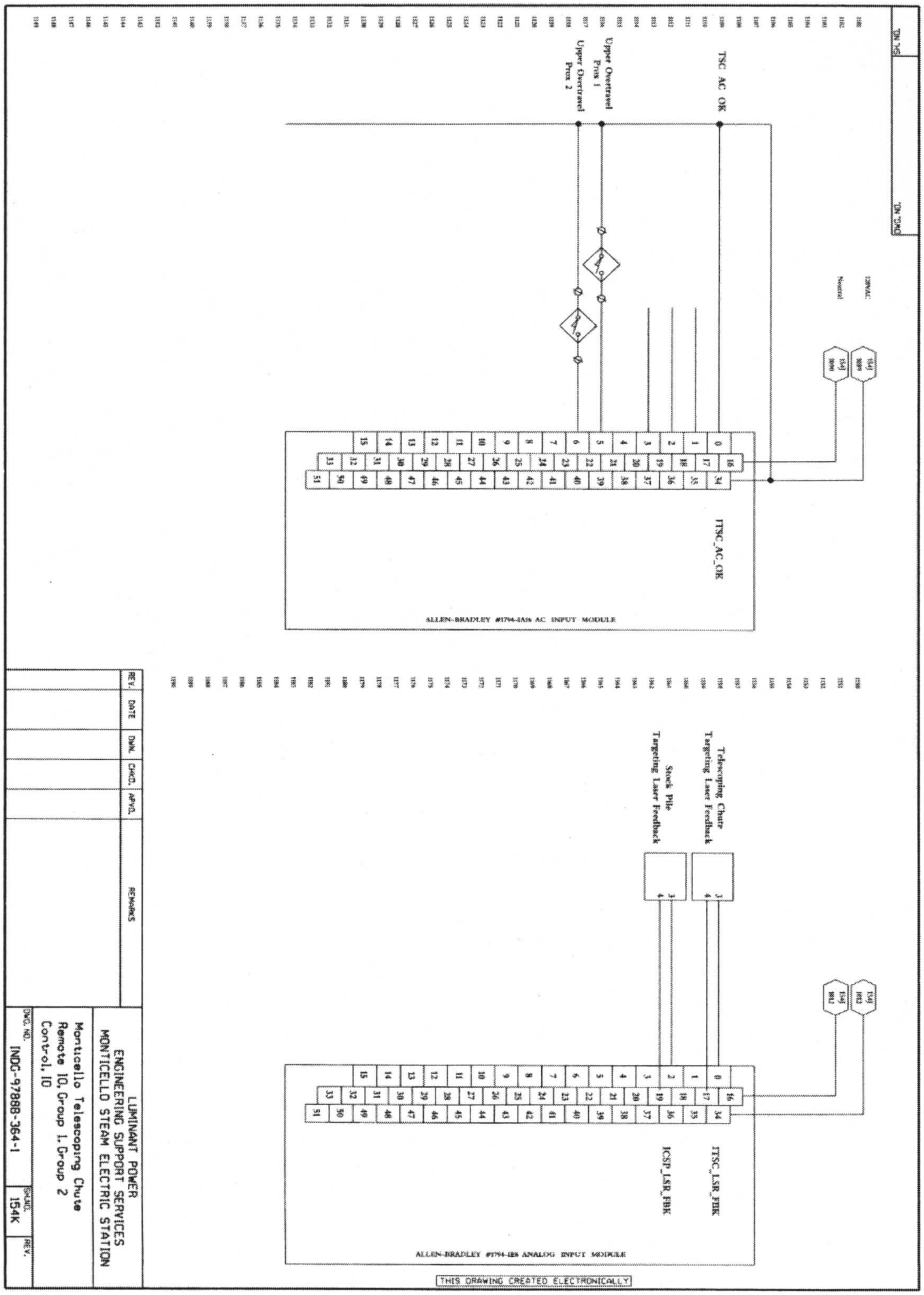
A - 9: Remote Slave Adapter Communications - A

Appendix A (Continued)



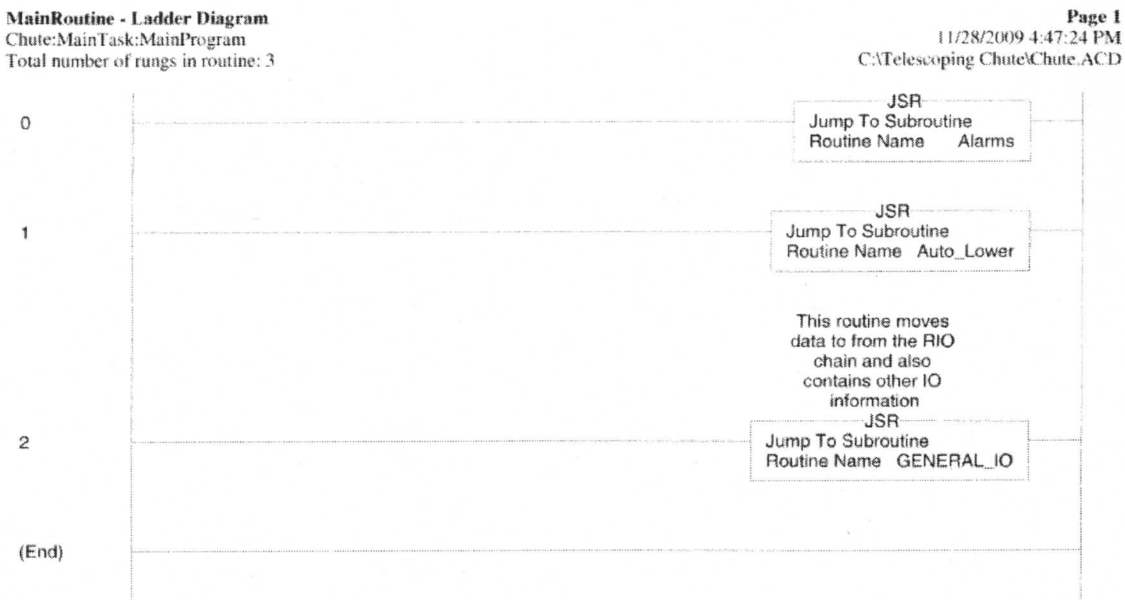
A - 10: Remote Slave IO - B

Appendix A (Continued)



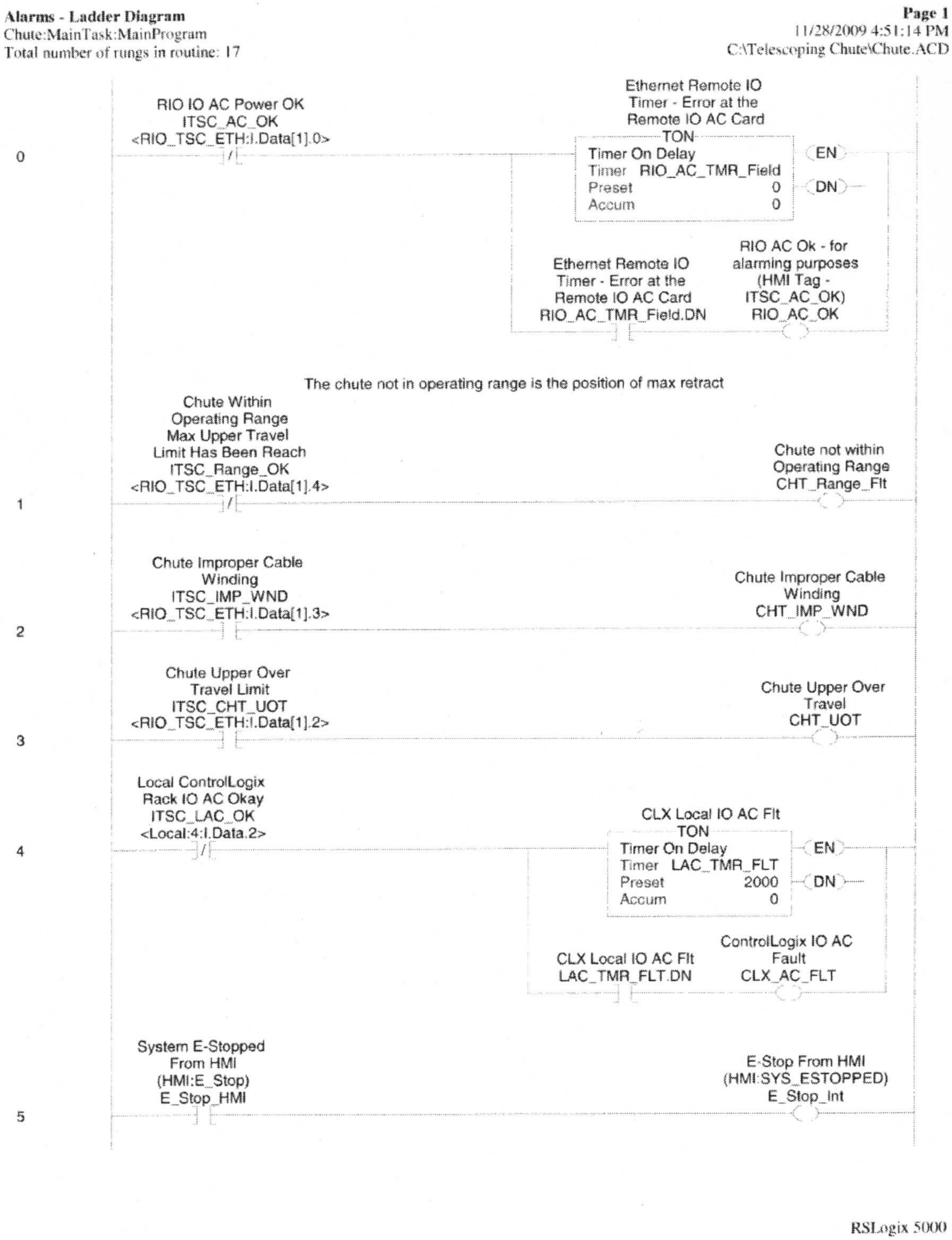
A - 11: Remote Slave IO and Analog Input

Appendix B – Laser Project ControlLogix Routines



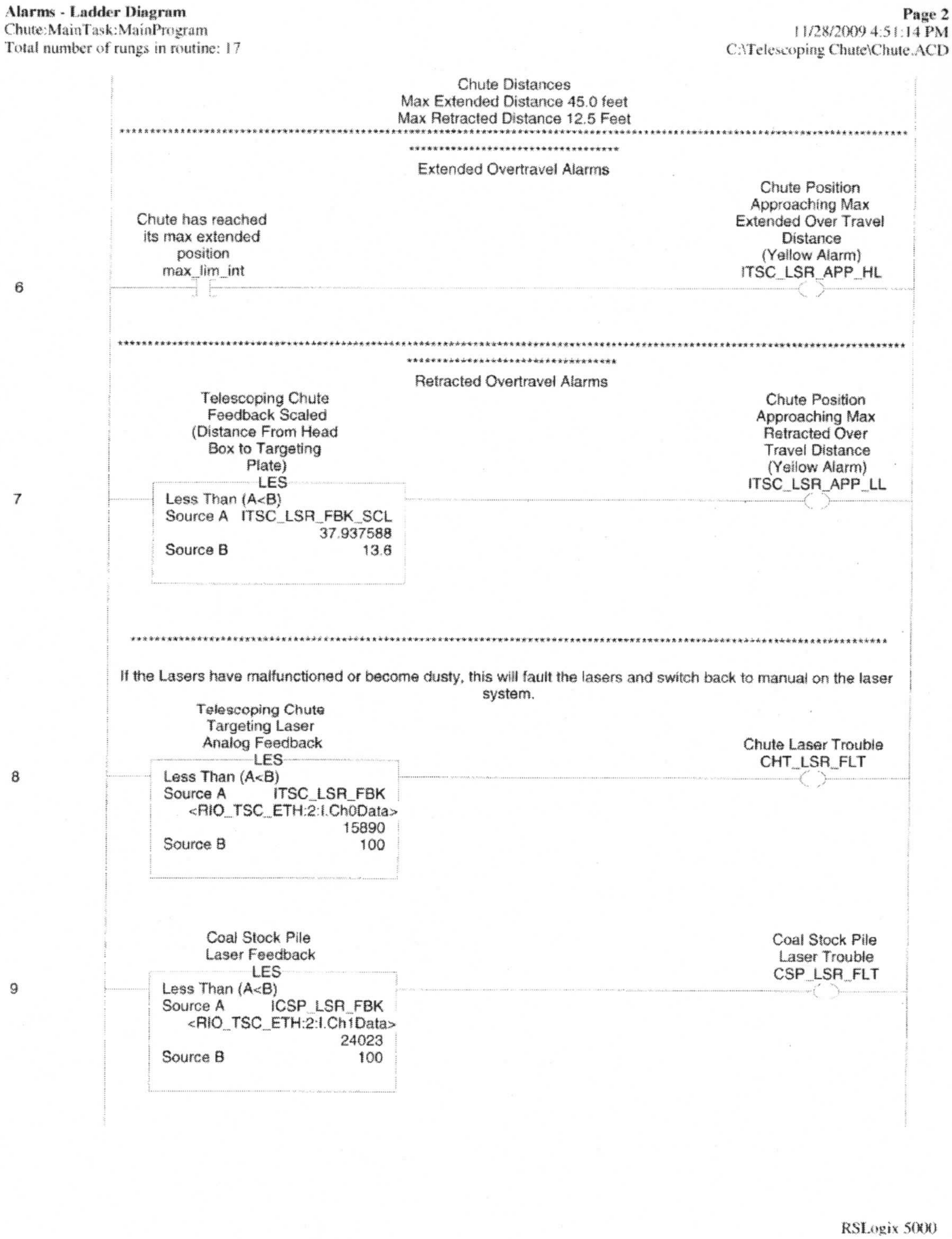
B - 1: Main Ladder Routine

Appendix B (Continued)



B - 2: Alarm Ladder Routine

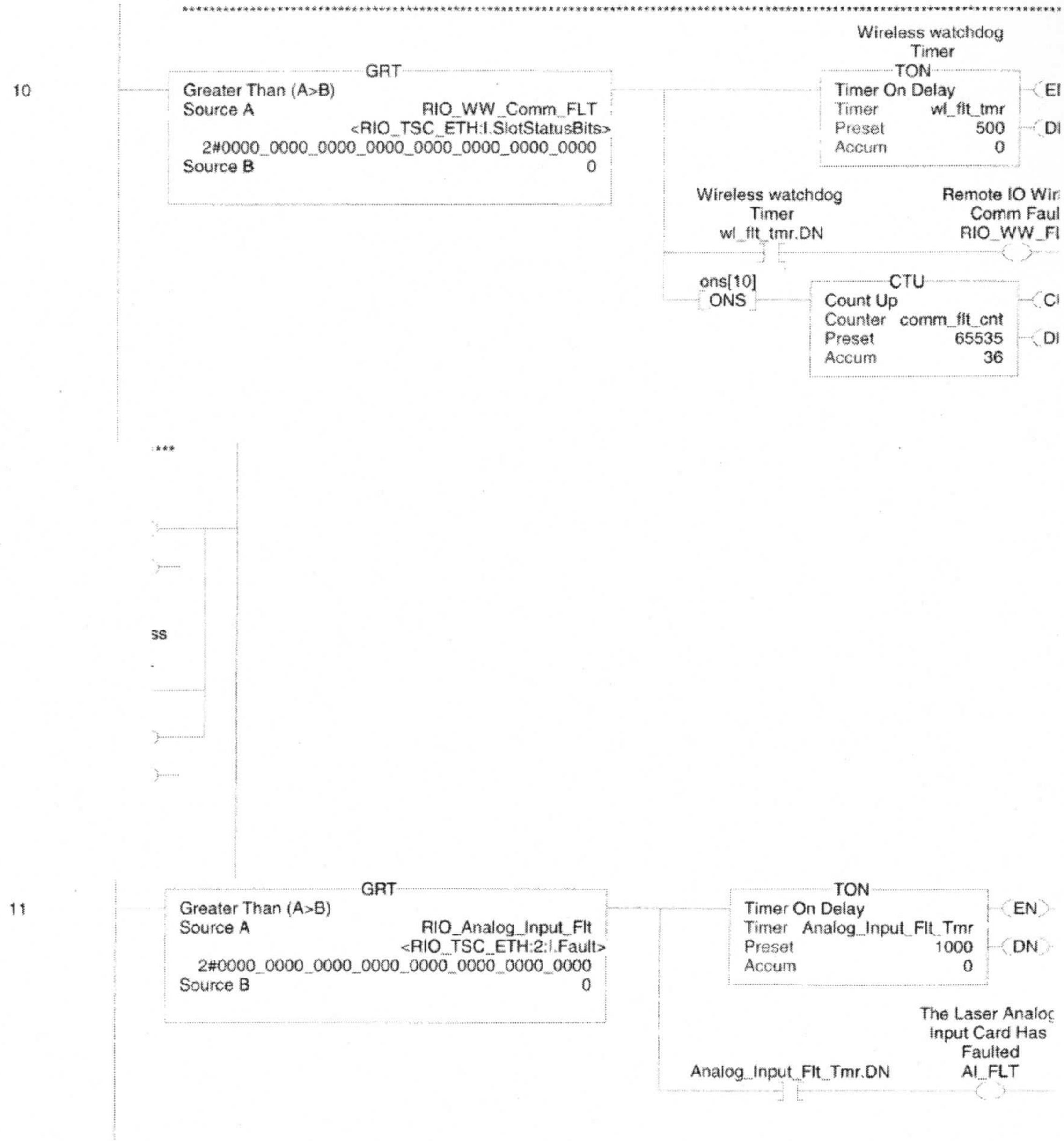
Appendix B (Continued)



B - 3: Alarm Ladder Routine

Appendix B (Continued)

Alarms - Ladder Diagram **Page 3**
Chute:MainTask:MainProgram 11/28/2009 4:51:14 PM
Total number of rungs in routine: 17 C:\Telescoping Chute\Chute.ACD



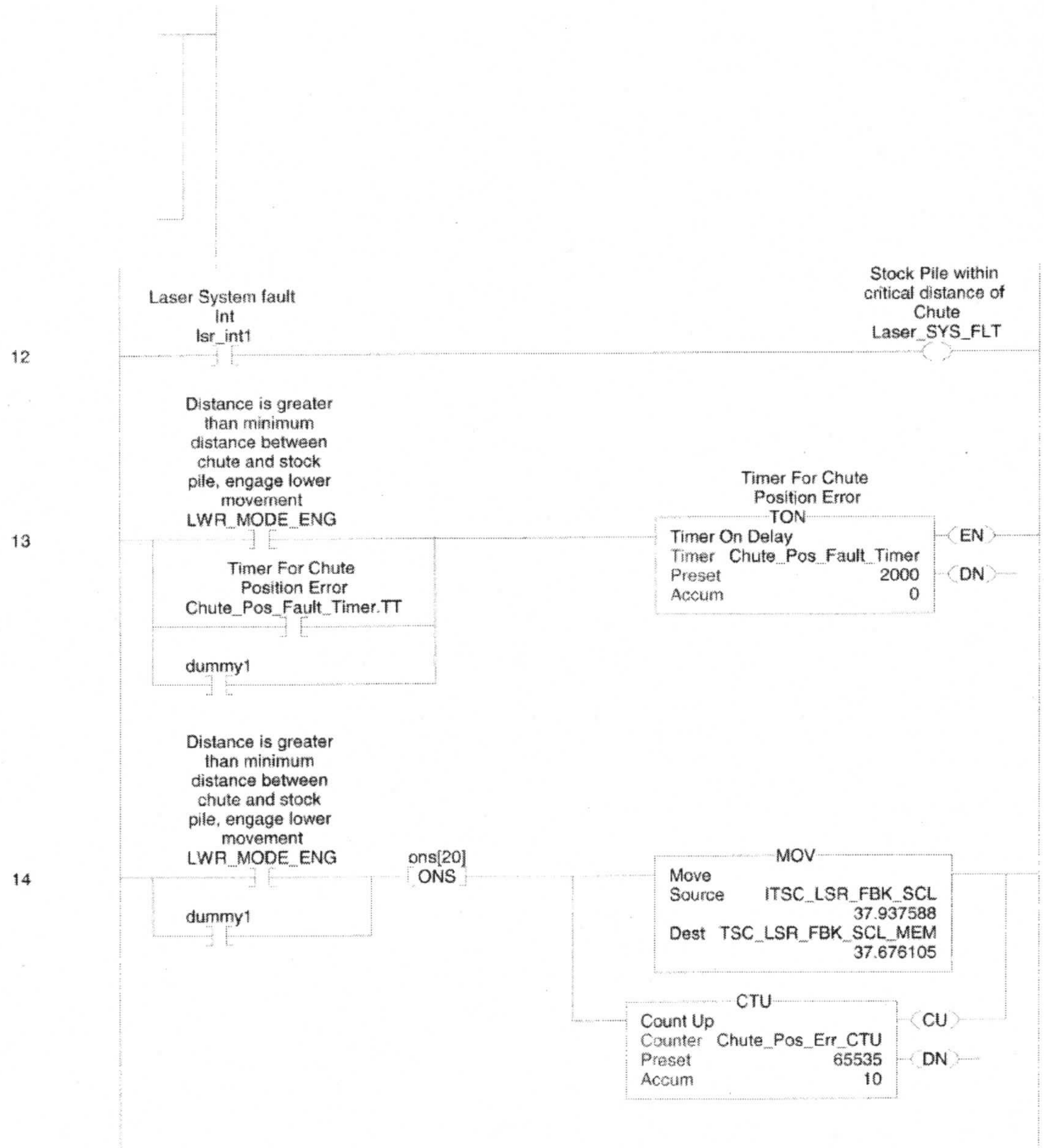
RSLogix 5000

B - 4: Alarm Ladder Routine

Appendix B (Continued)

Alarms - Ladder Diagram
Chute:MainTask:MainProgram
Total number of rungs in routine: 17

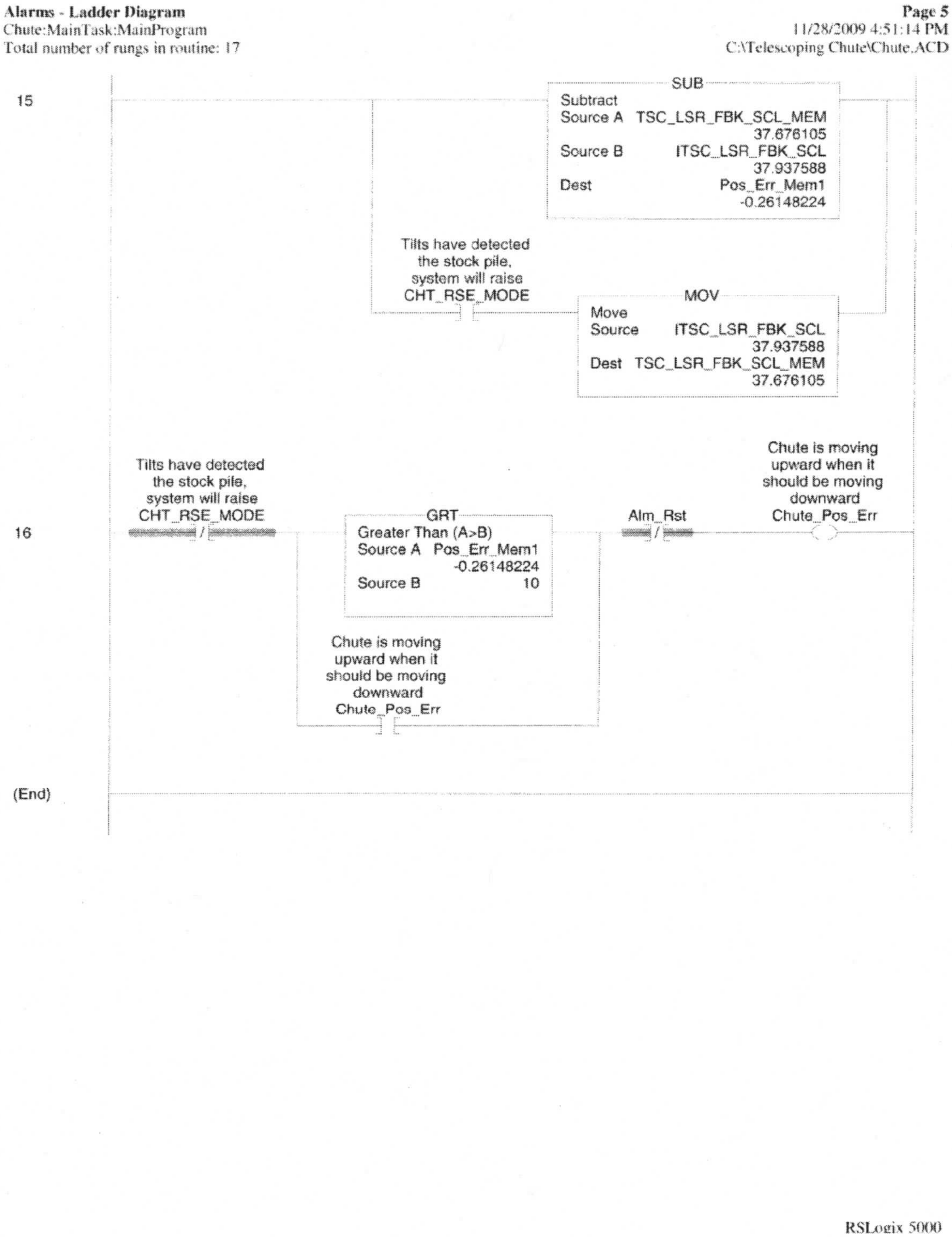
Page 4
11/28/2009 4:51:14 PM
C:\Telescoping Chute\Chute.ACD



RSLogix 5000

B - 5: Alarm Ladder Routine

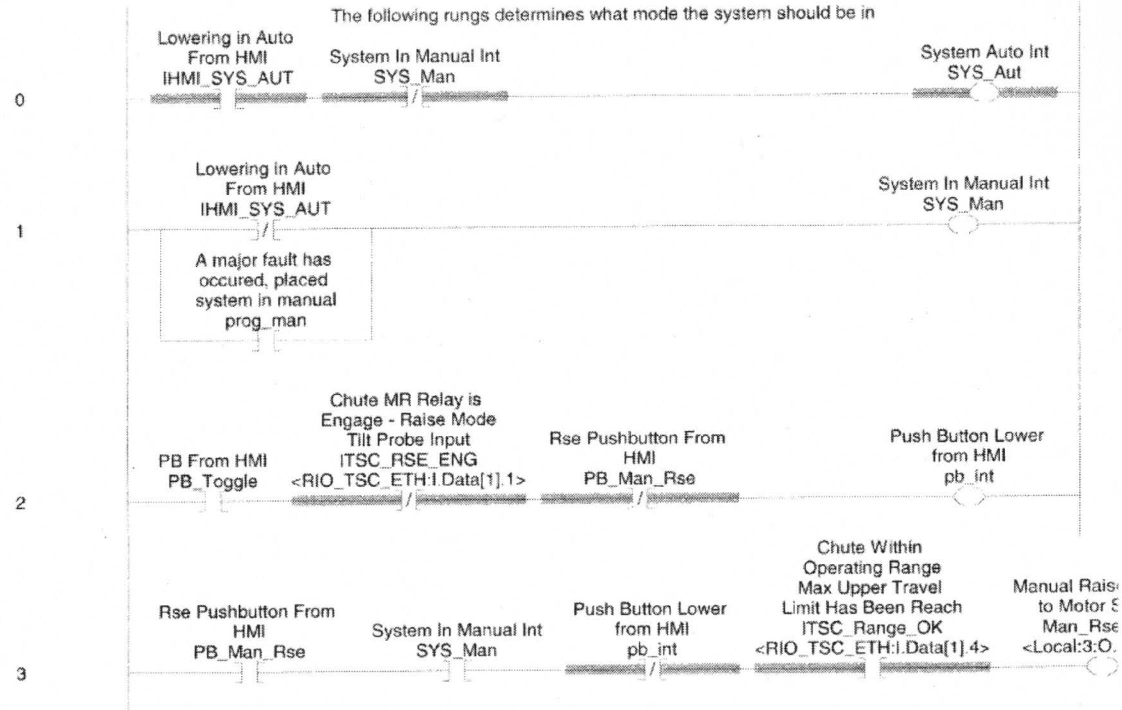
Appendix B (Continued)



B - 6: Alarm Ladder Routine

Appendix B (Continued)

Auto_Lower - Ladder Diagram | **Page 1**
Chute:MainTask:MainProgram | 11/28/2009 4:51:37 PM
Total number of rungs in routine: 23 | C:\Telescoping Chute\Chute.ACD

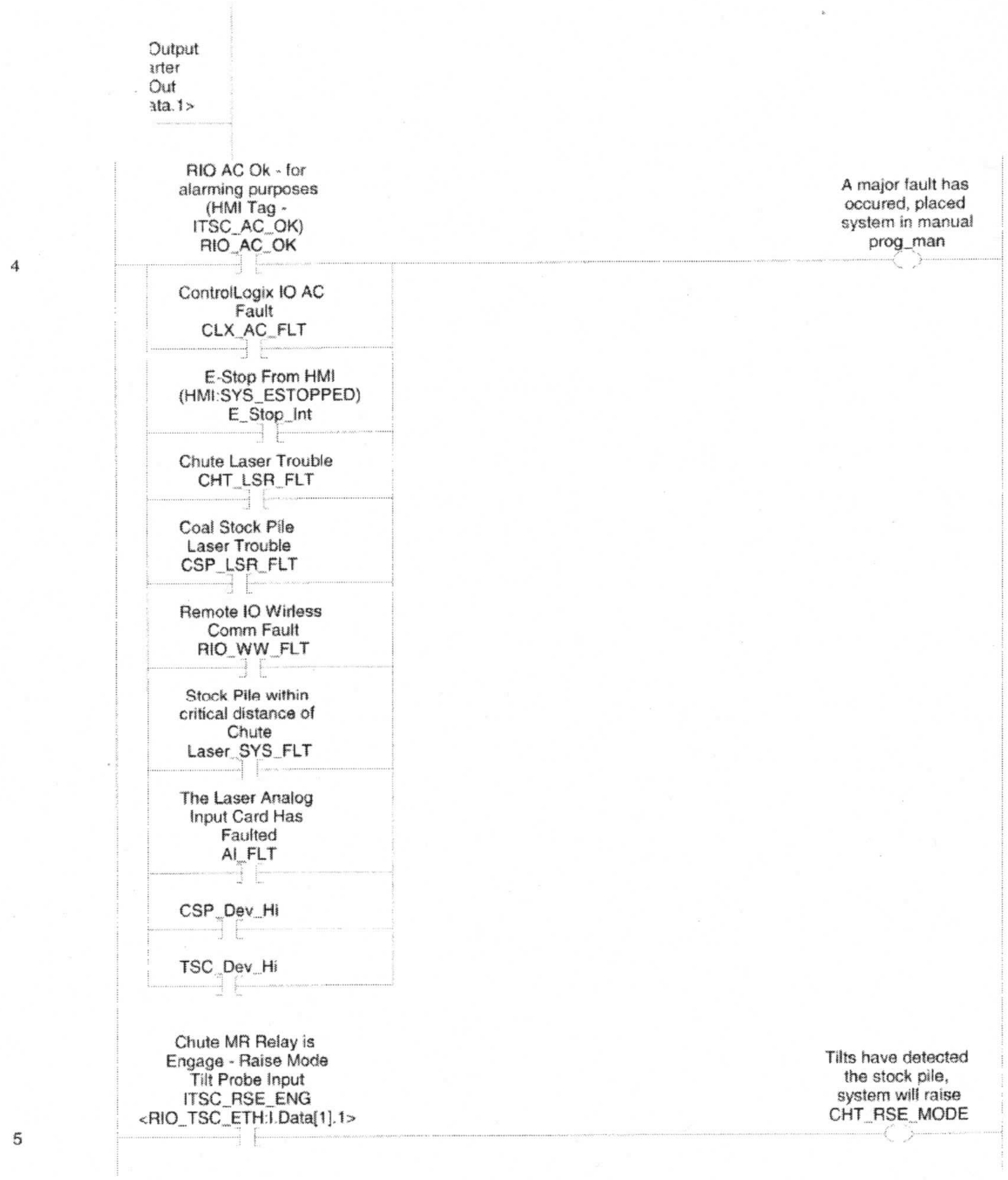


RSLogix 5000

B - 7: Auto Lower Routine

Auto_Lower - Ladder Diagram
Chute:MainTask:MainProgram
Total number of rungs in routine: 23

Page 2
11/28/2009 4:51:37 PM
C:\Telescoping Chute\Chute.ACD



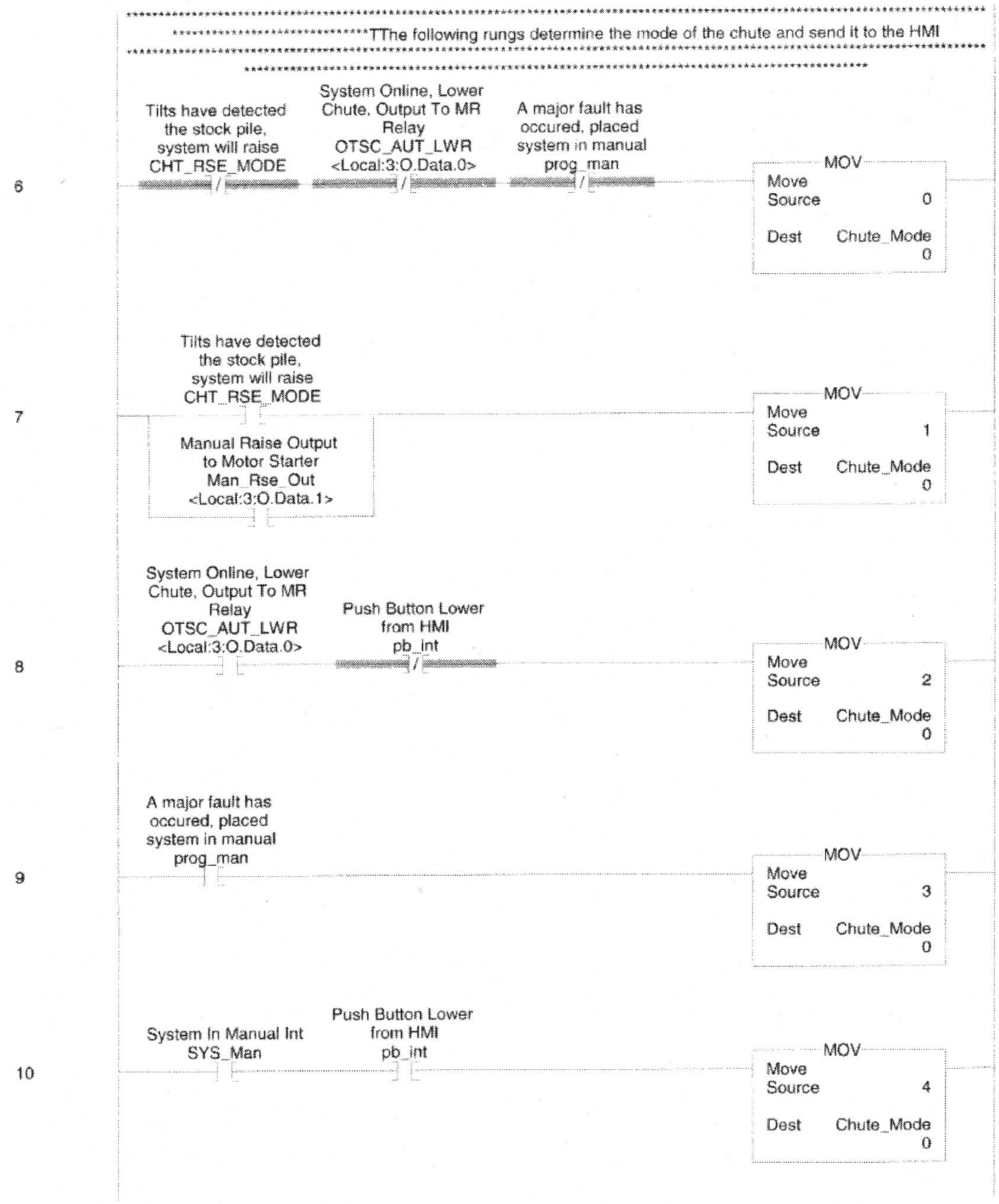
RSLogix 5000

B - 8: Auto Lower Routine

Appendix B (Continued)

Auto_Lower - Ladder Diagram
Chute:MainTask:MainProgram
Total number of rungs in routine: 23

Page 3
11/28/2009 4:51:37 PM
C:\Telescoping Chute\Chute.ACD



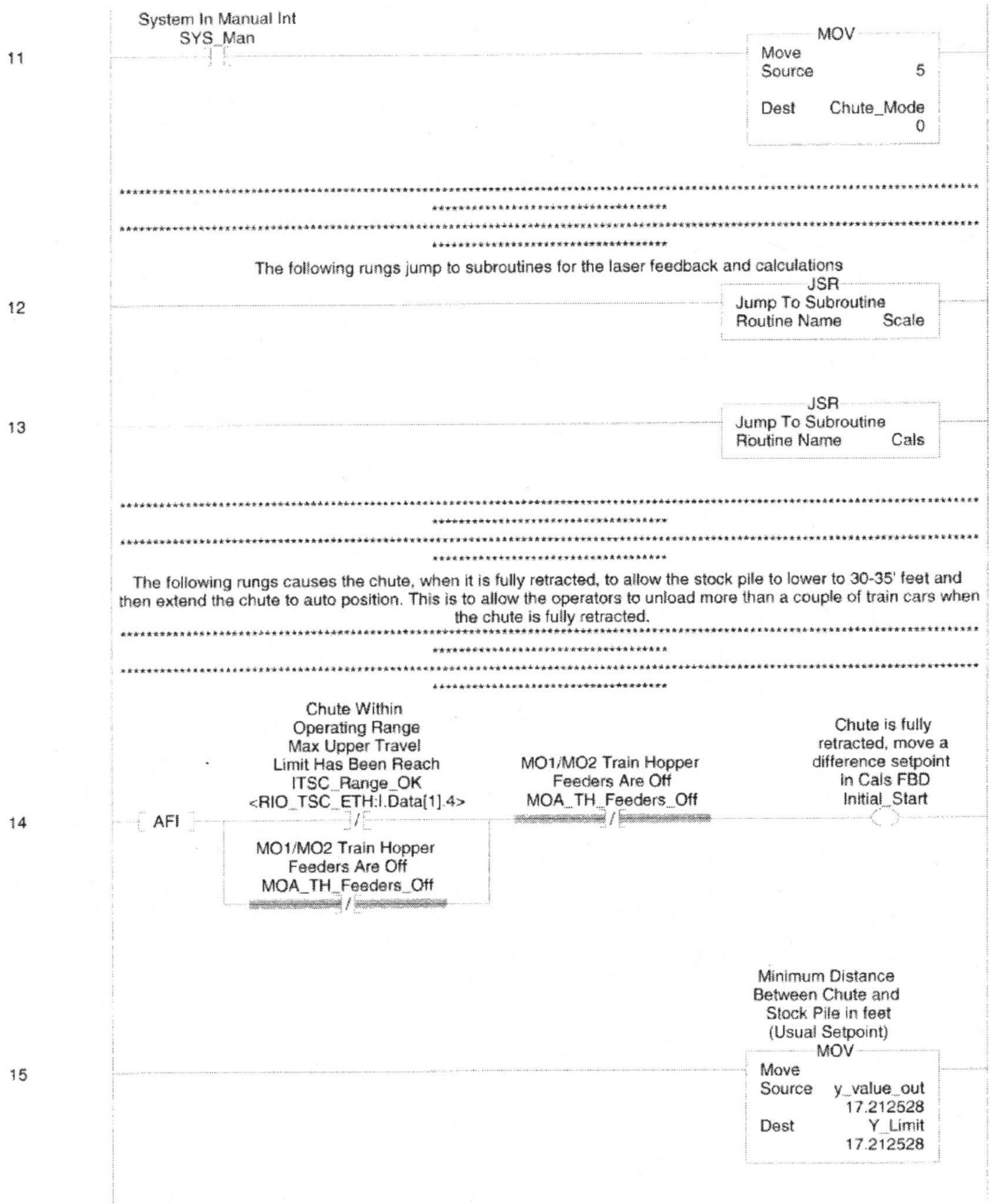
RSLogix 5000

B - 9: Auto Lower Routine

Appendix B (Continued)

Auto_Lower - Ladder Diagram
Chute:MainTask:MainProgram
Total number of rungs in routine: 23

Page 4
11/28/2009 4:51:37 PM
C:\Telescoping Chute\Chute.ACD



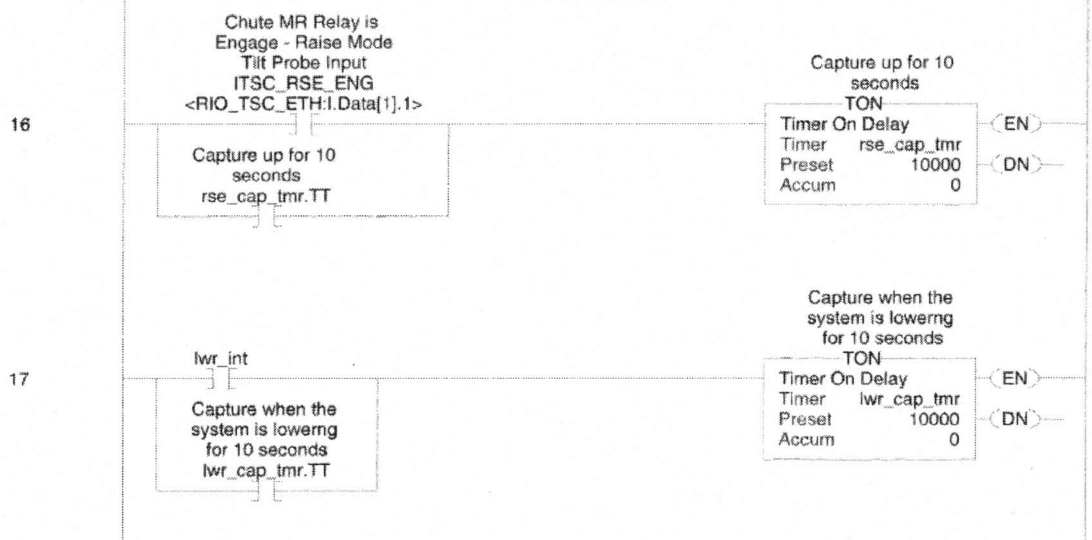
RSLogix 5000

B - 10: Auto Lower Routine

Appendix B (Continued)

Auto_Lower - Ladder Diagram | **Page 5**
Chute:MainTask:MainProgram | 11/28/2009 4:51:39 PM
Total number of rungs in routine: 23 | C:\Telescoping Chute\Chute.ACD

The following rungs capture when the chute is trying to logically move down and the tilt probes are detecting the stock pile at the same time. Therefore, a new setpoint is moved into the lowering functioning blocks.

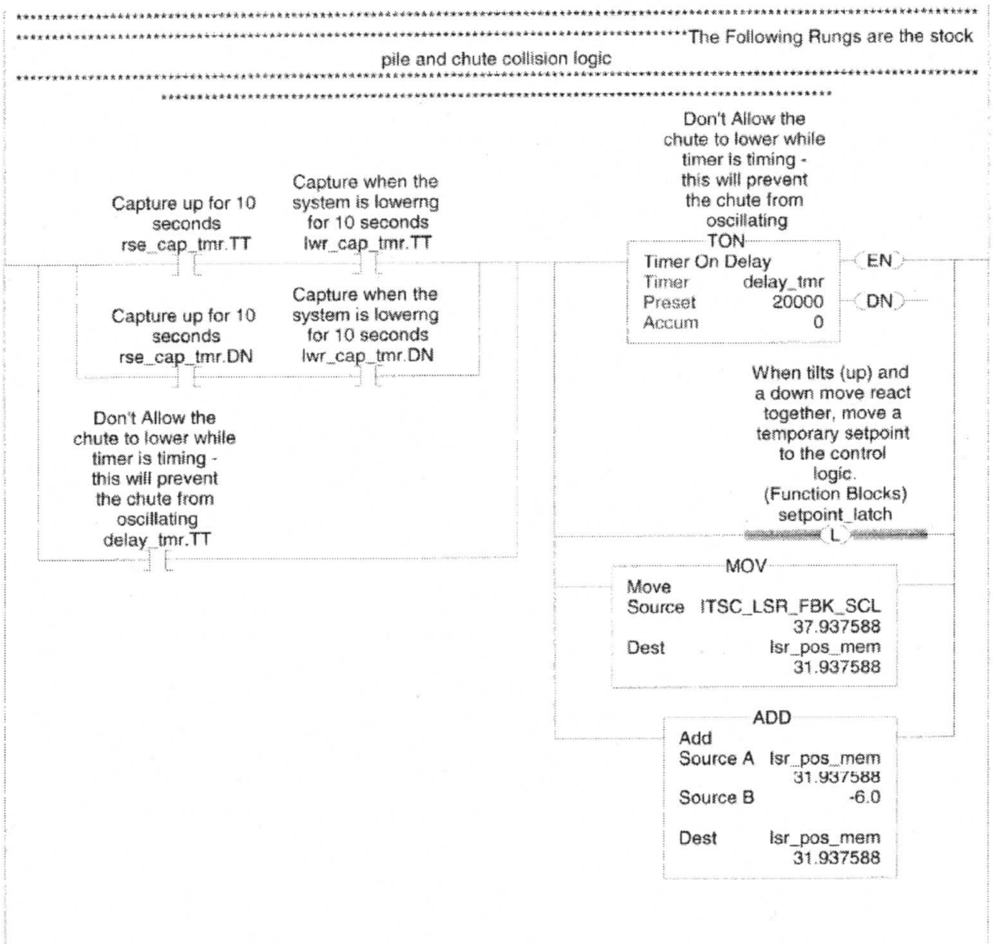


RSLogix 5000

B - 11: Auto Lower Routine

Auto_Lower - Ladder Diagram
Chute:MainTask:MainProgram
Total number of rungs in routine: 23

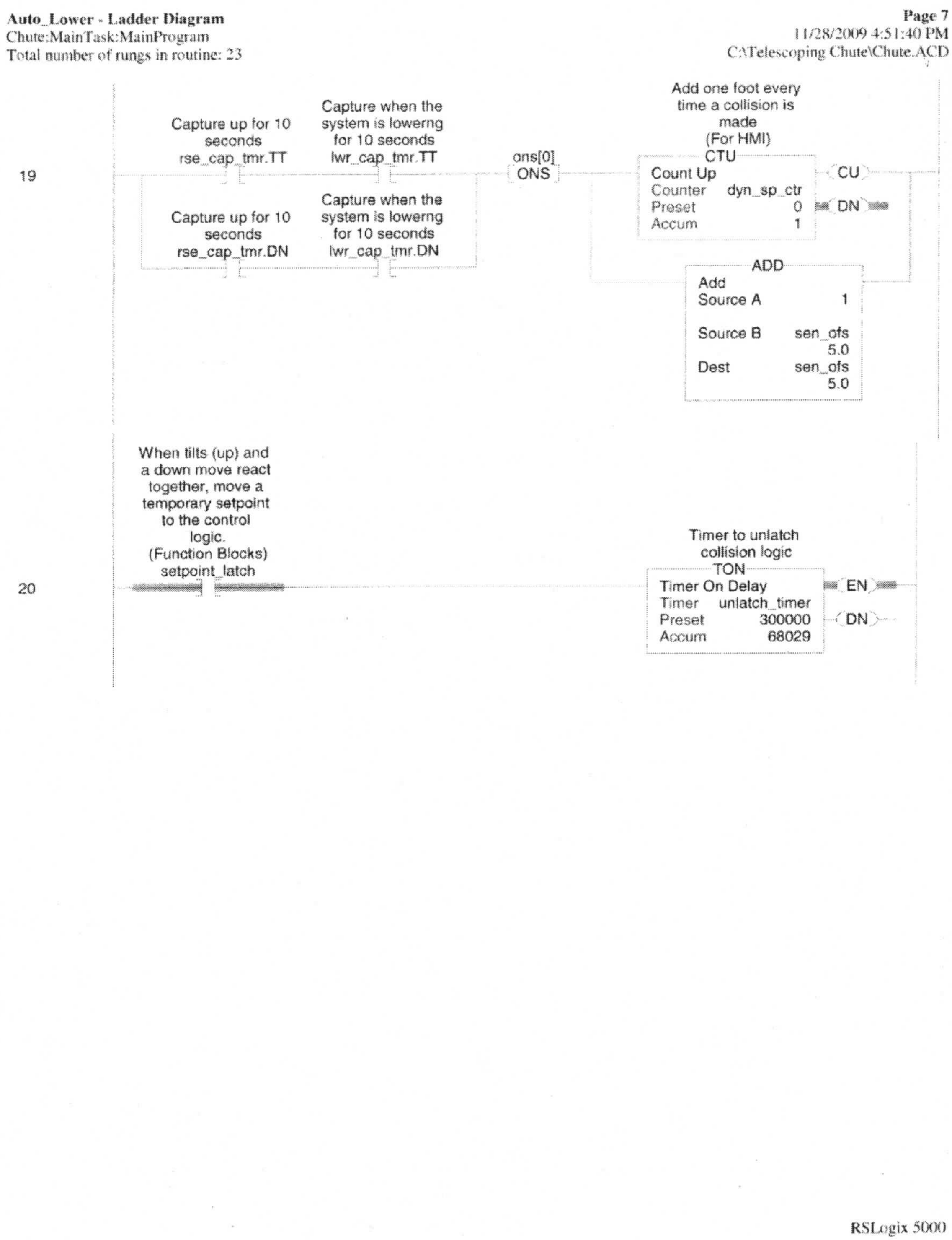
Page 6
11/28/2009 4:51:39 PM
C:\Telescoping Chute\Chute.ACD



RSLogix 5000

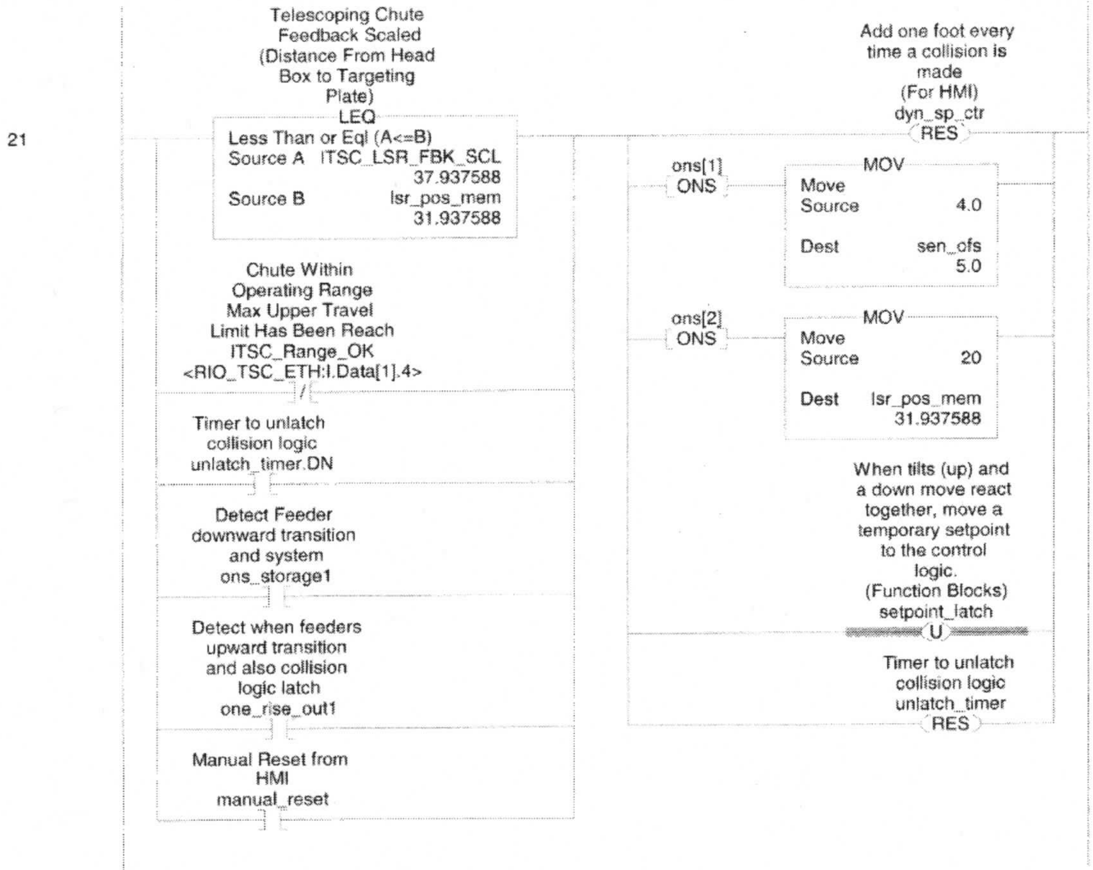
B - 12: Auto Lower Routine

Appendix B (Continued)



B - 13: Auto Lower Routine

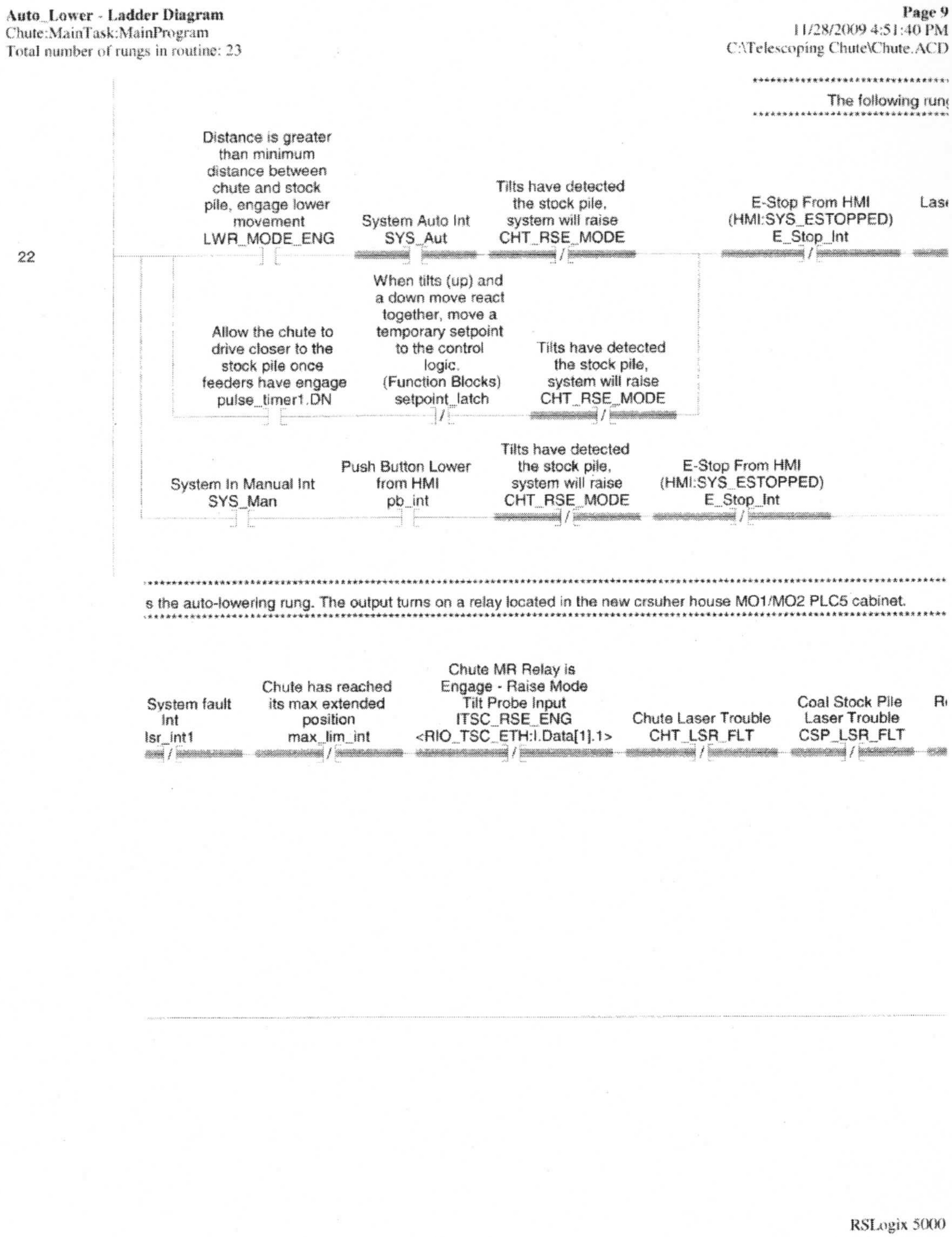
Auto_Lower - Ladder Diagram **Page 8**
Chute:MainTask:MainProgram 11/28/2009 4:51:40 PM
Total number of rungs in routine: 23 C:\Telescoping Chute\Chute.ACD



RSLogix 5000

B - 14: Auto Lower Routine

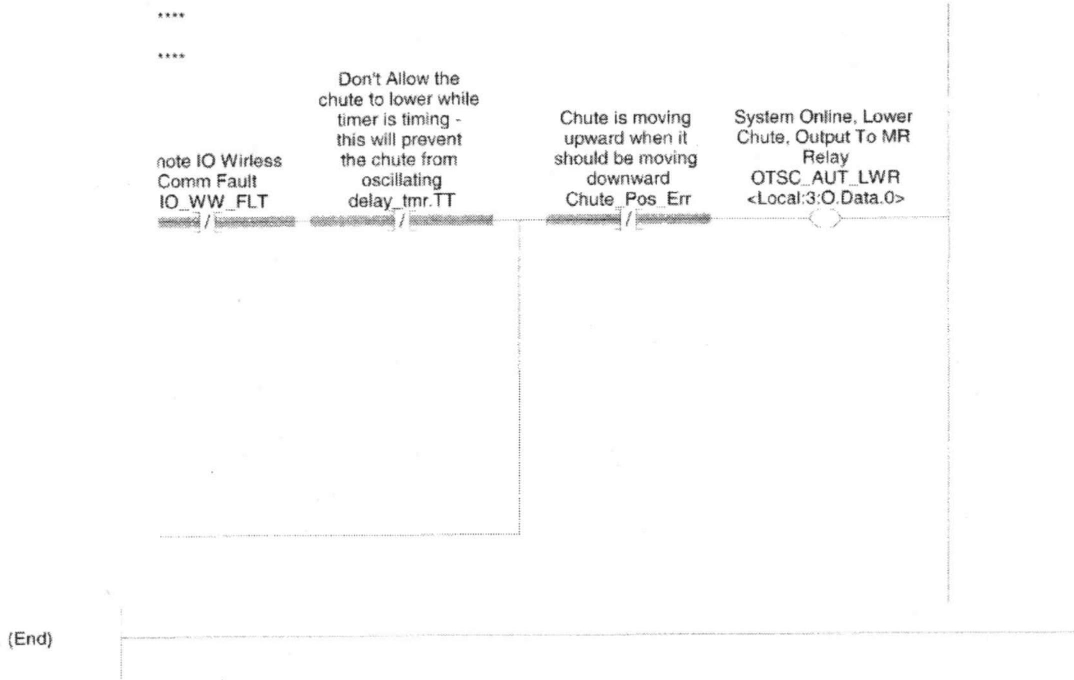
Appendix B (Continued)



B - 15: Auto Lower Routine

Auto_Lower - Ladder Diagram
Chute:MainTask:MainProgram
Total number of rungs in routine: 23

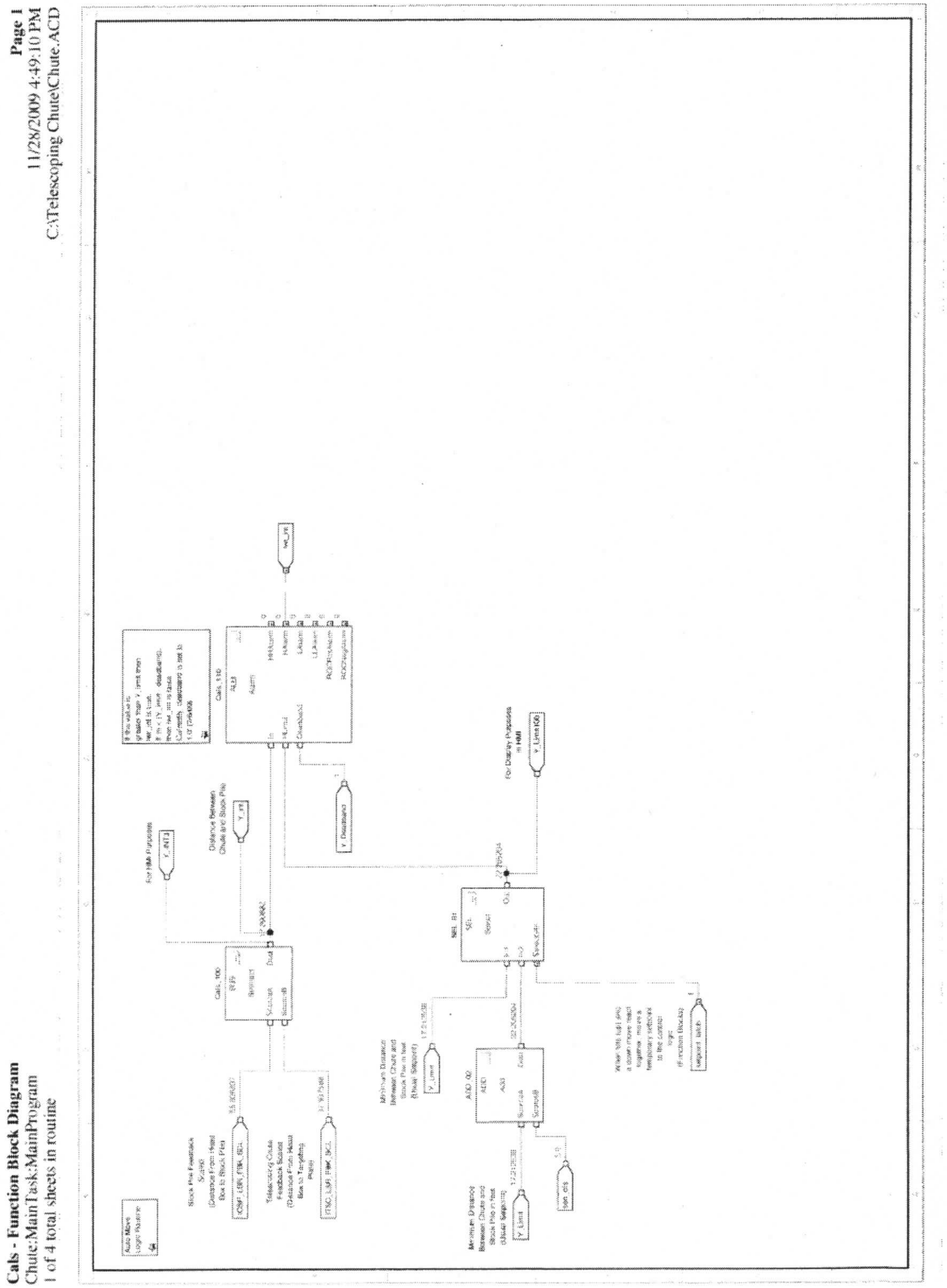
Page 10
11/28/2009 4:51:40 PM
C:\Telescoping Chute\Chute.ACD



RSLogix 5000

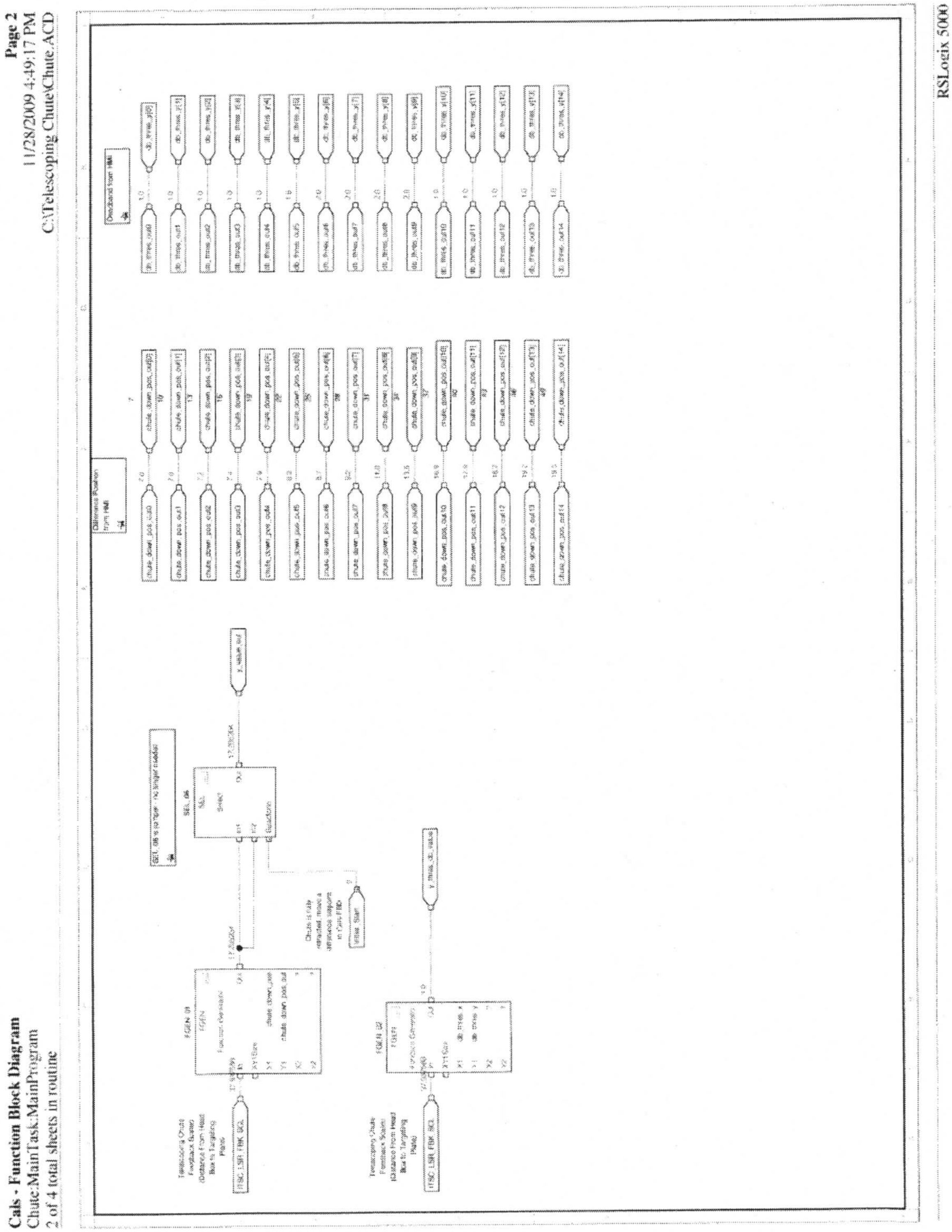
B - 16: Auto Lower Routine

Appendix B (Continued)



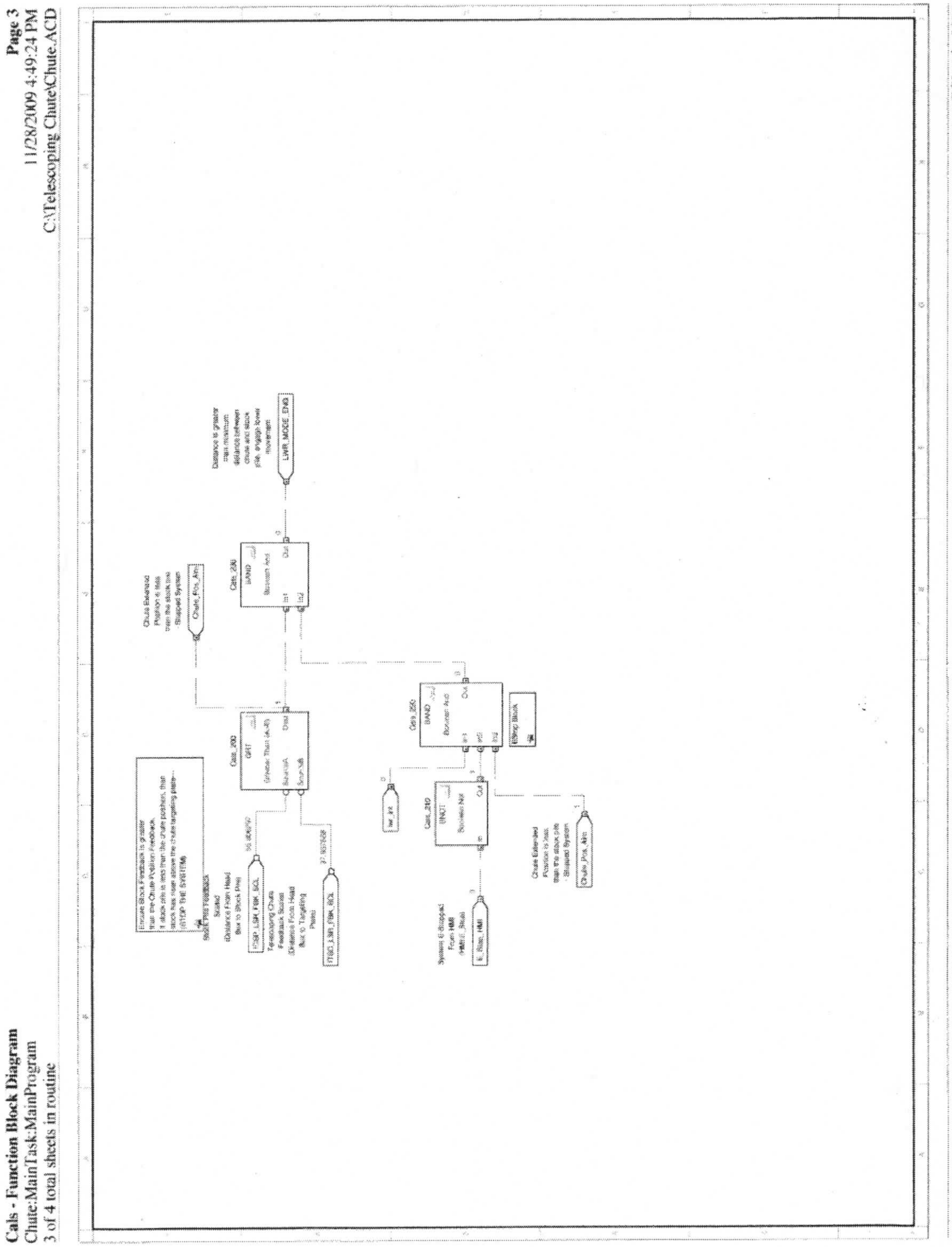
B - 17: Setpoint Management Routine

Appendix B (Continued)



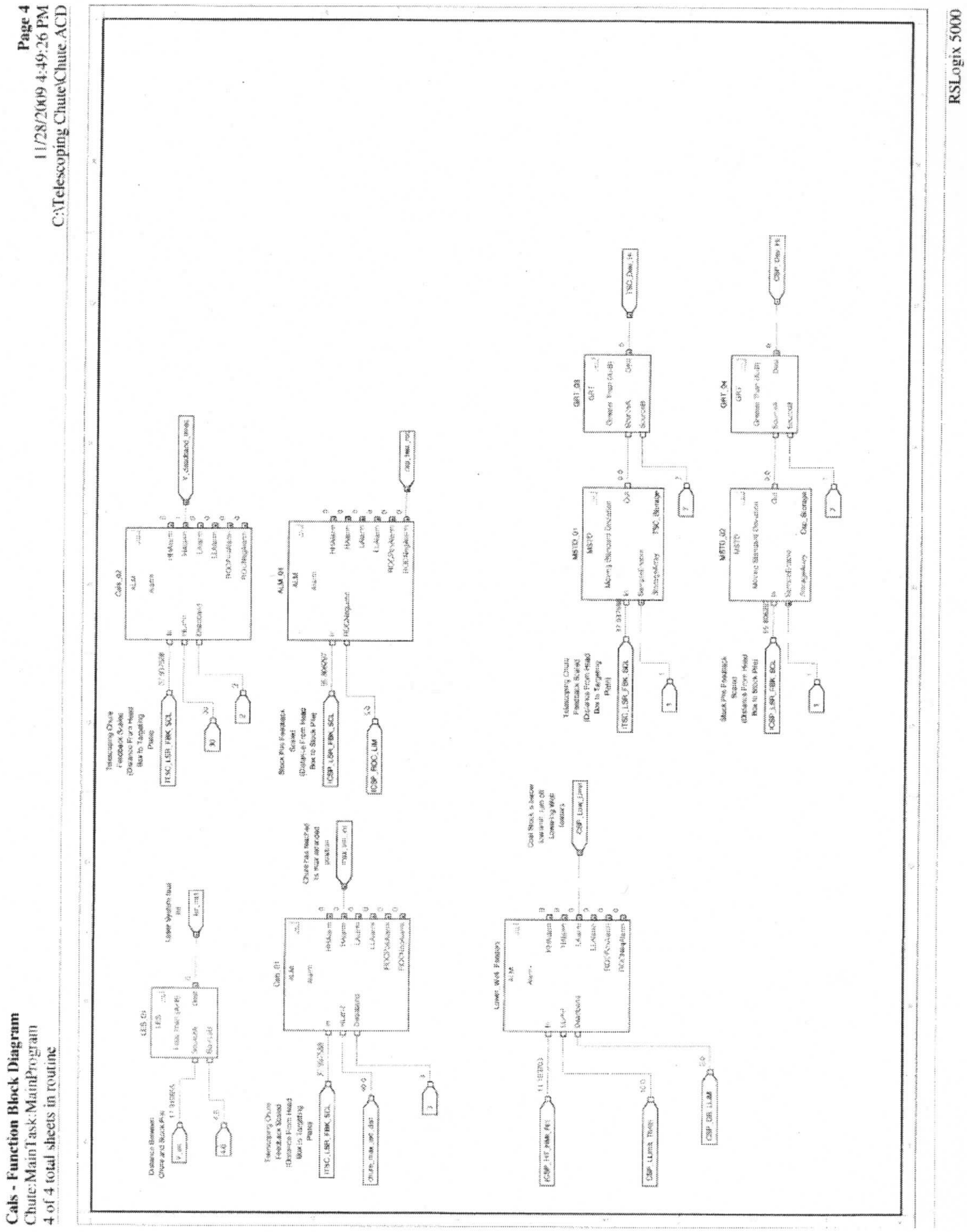
B - 18: Setpoint Management Routine

Appendix B (Continued)



B - 19: Setpoint Management Routine

Appendix B (Continued)



B - 20: Setpoint Management Routine

Appendix B (Continued)

GENERAL_IO - Ladder Diagram
Chute:MainTask:MainProgram
Total number of rungs in routine: 20

Page 1
11/28/2009 4:53:05 PM
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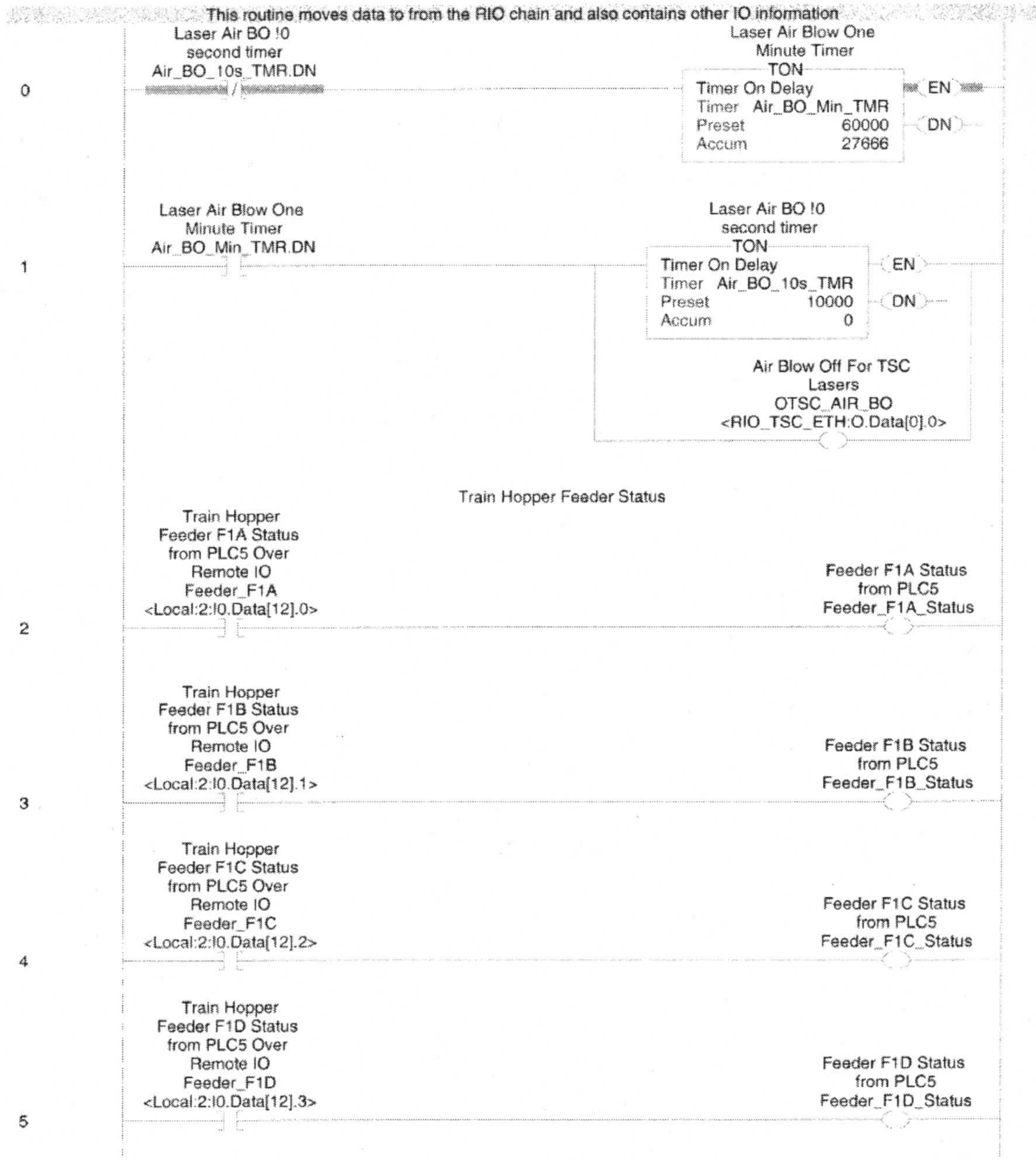
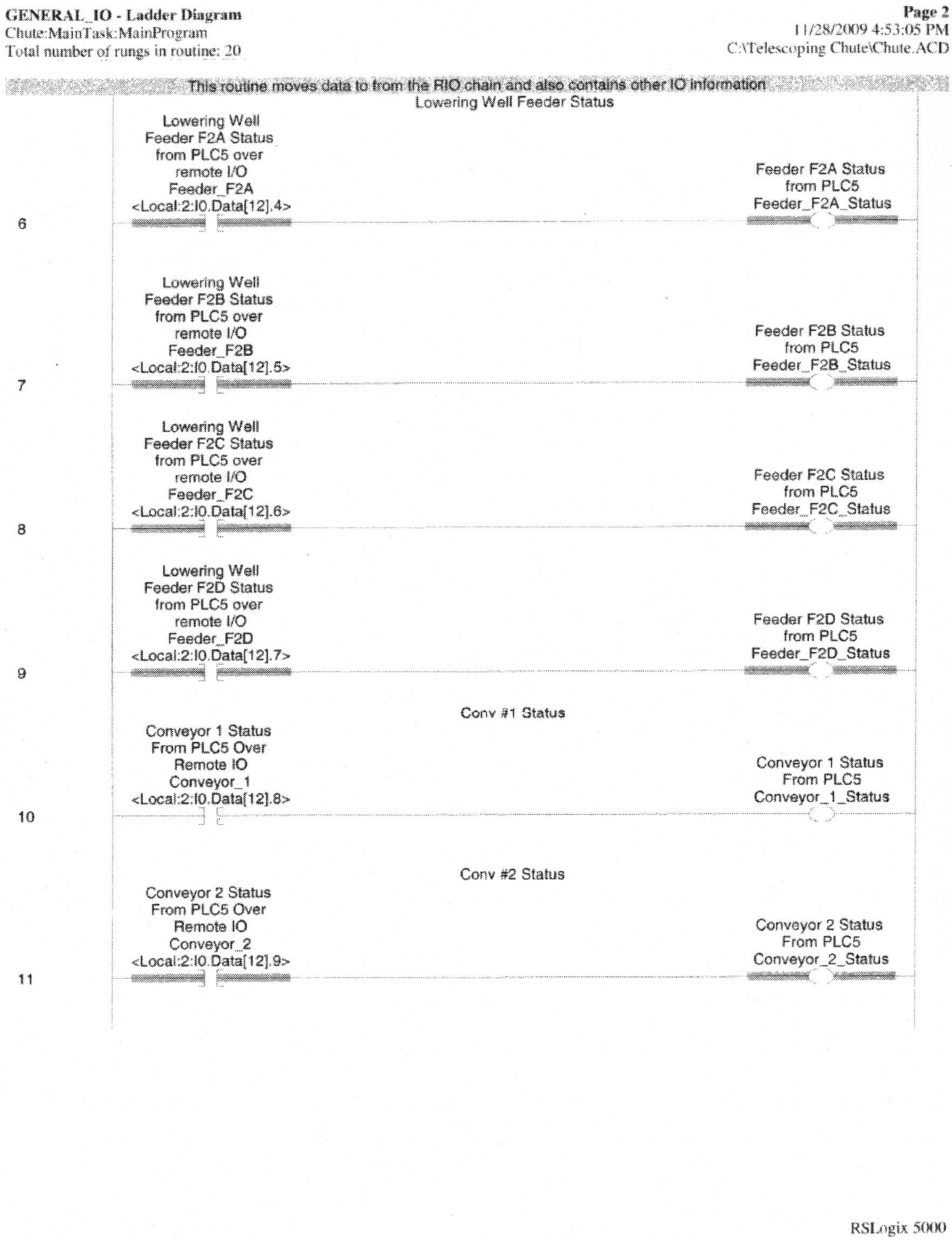


B - 21: General IO Routine

Appendix B (Continued)



B - 22: General IO Routine

Appendix B (Continued)

GENERAL_IO - Ladder Diagram
Chute:MainTask:MainProgram
Total number of rungs in routine: 20

Page 3
11/28/2009 4:53:05 PM
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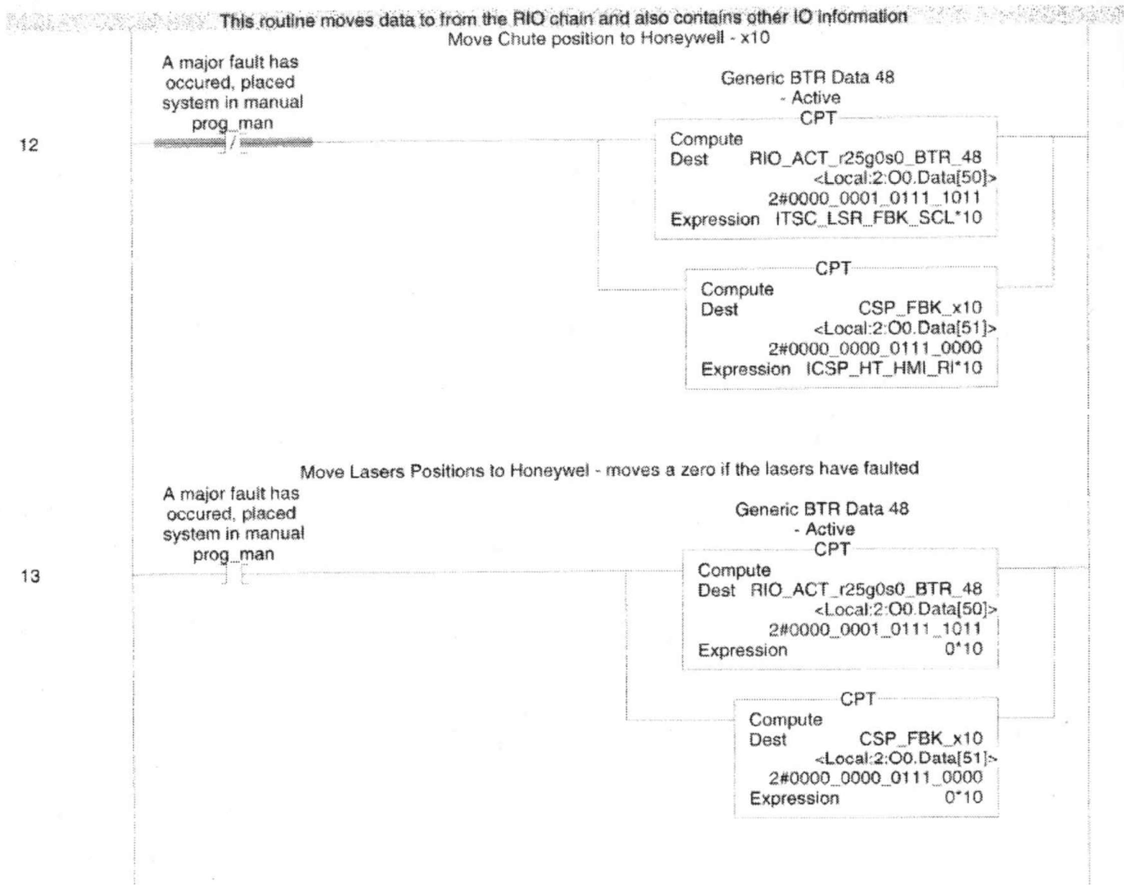
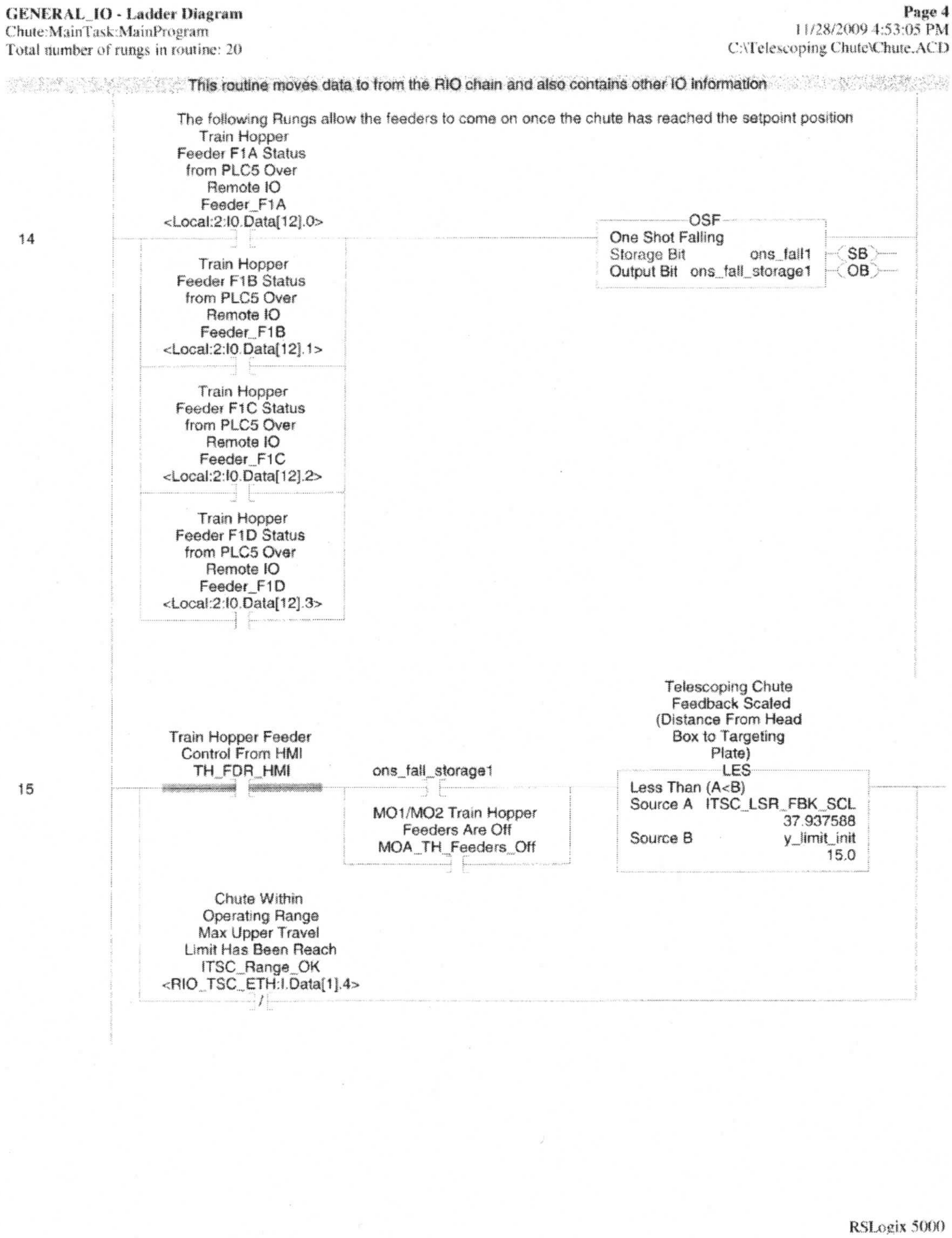


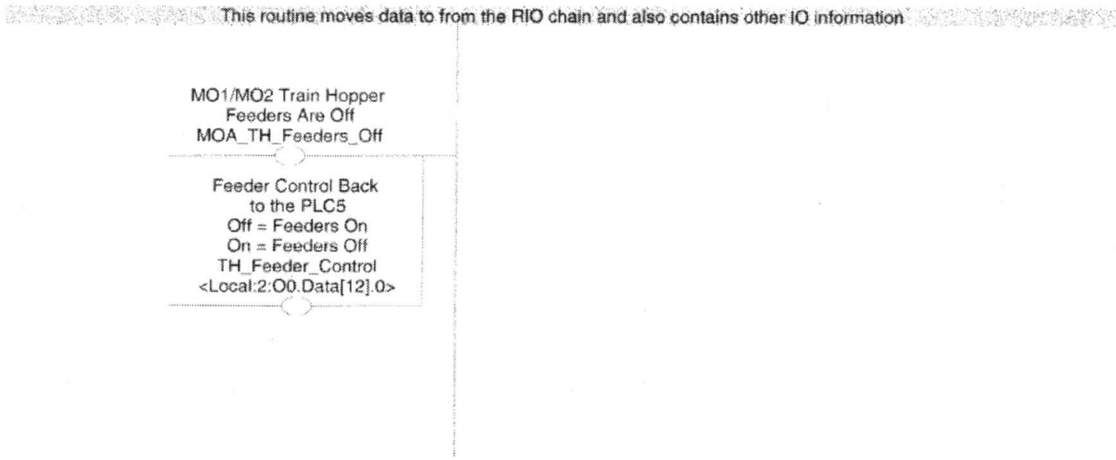
RSLogix 5000

B - 23: General IO Routine



B - 24: General IO Routine

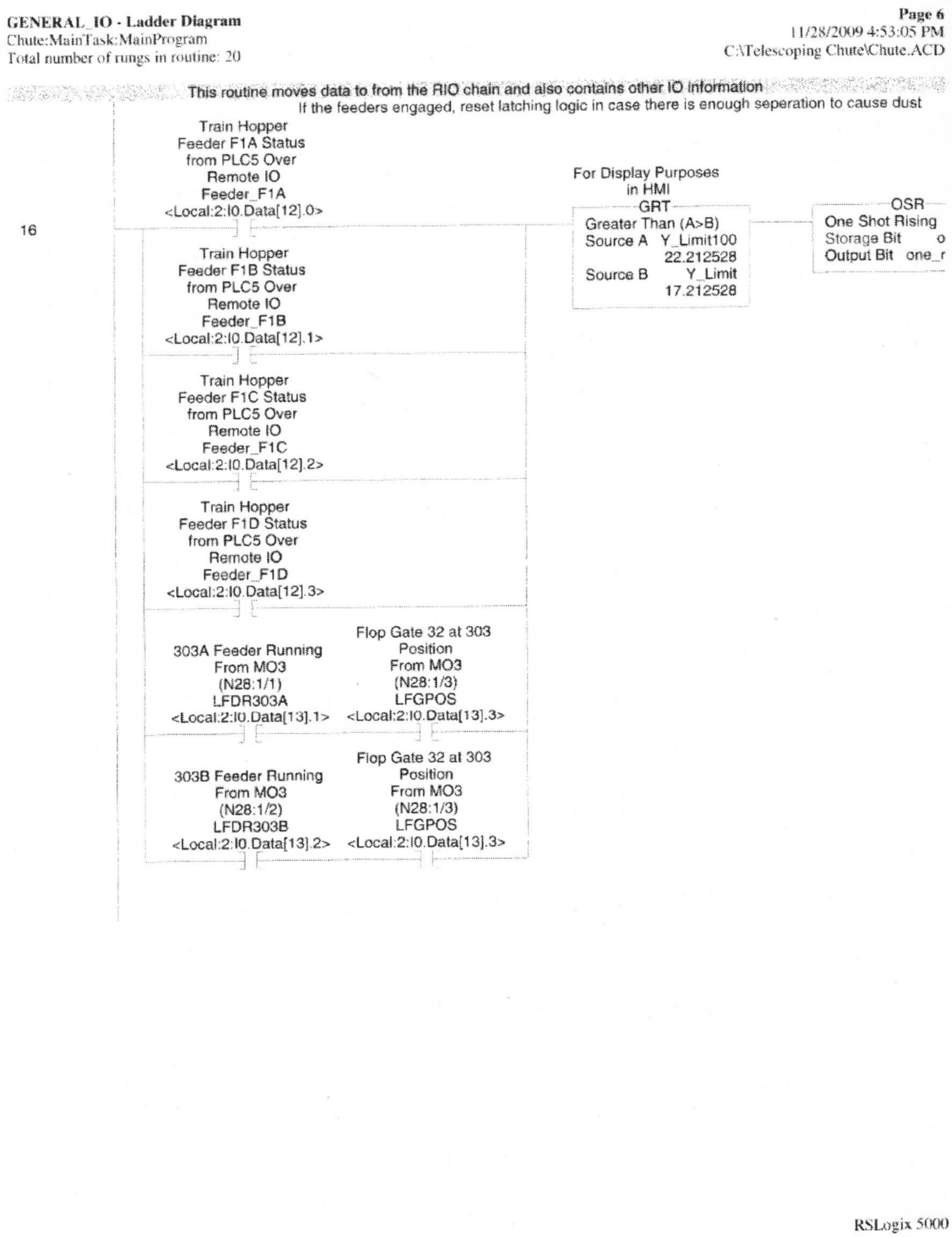
GENERAL_IO - Ladder Diagram **Page 5**
Chute:MainTask:MainProgram 11/28/2009 4:53:05 PM
Total number of rungs in routine: 20 C:\Telescoping Chute\Chute.ACD



RSLogix 5000

B - 25: General IO Routine

Appendix B (Continued)



B - 26: General IO Routine

Appendix B (Continued)

GENERAL_IO - Ladder Diagram
Chute:MainTask:MainProgram
Total number of rungs in routine: 20

Page 7
11/28/2009 4:53:05 PM
C:\Telescoping Chute\Chute.ACD

This routine moves data to from the RIO chain and also contains other IO information

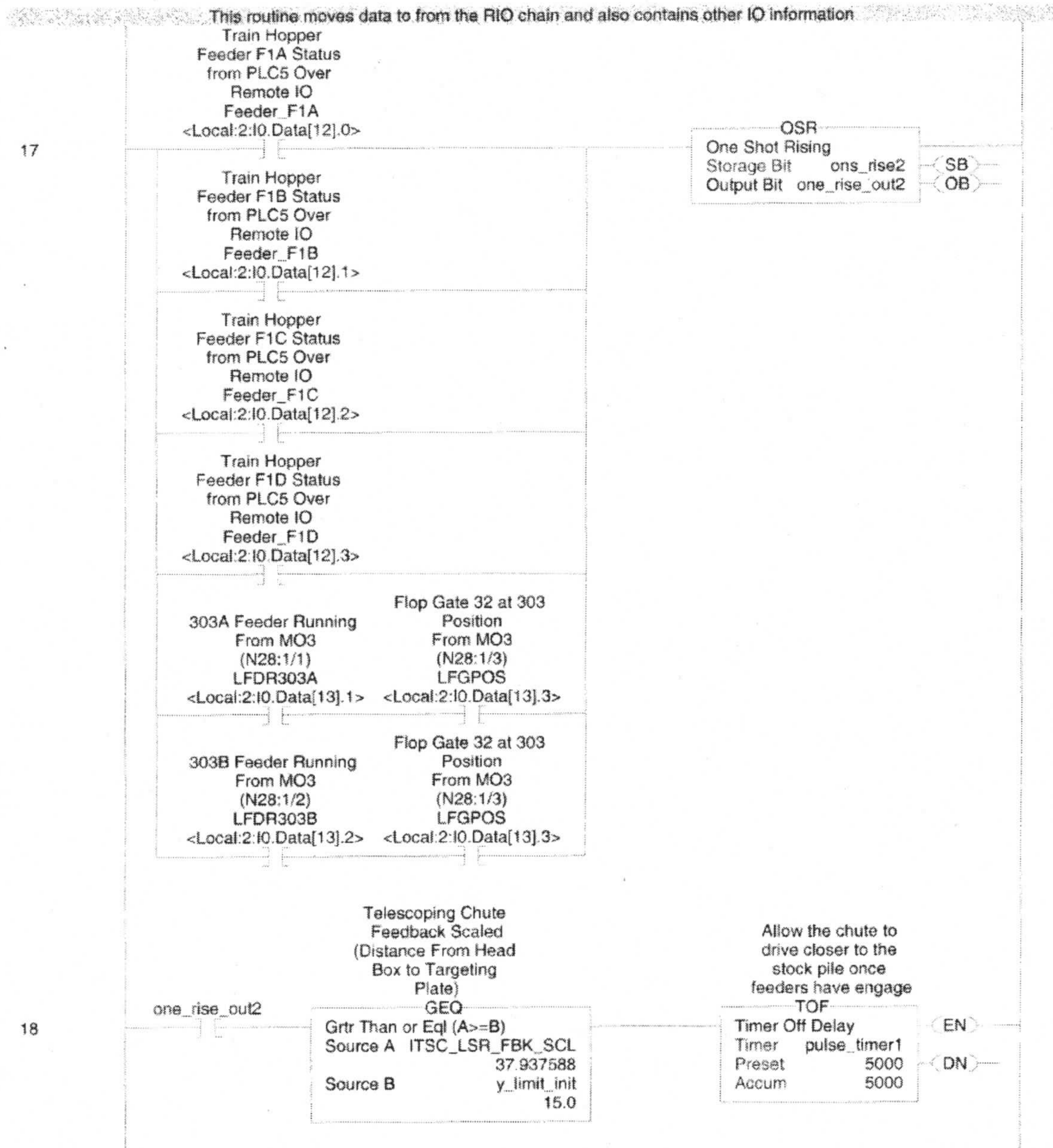
RSLogix 5000

B - 27: General IO Routine

Appendix B (Continued)

GENERAL_IO - Ladder Diagram
Chute:MainTask:MainProgram
Total number of rungs in routine: 20

Page 8
11/28/2009 4:53:05 PM
C:\Telescoping Chute\Chute.ACD



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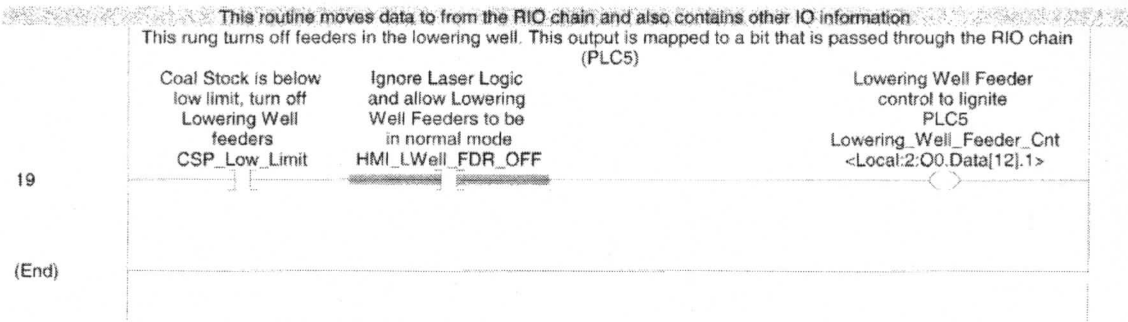
B - 28: General IO Routine

GENERAL_IO - Ladder Diagram **Page 9**
Chute:MainTask:MainProgram 11/28/2009 4:53:06 PM
Total number of rungs in routine: 20 C:\Telescoping Chute\Chute.ACD



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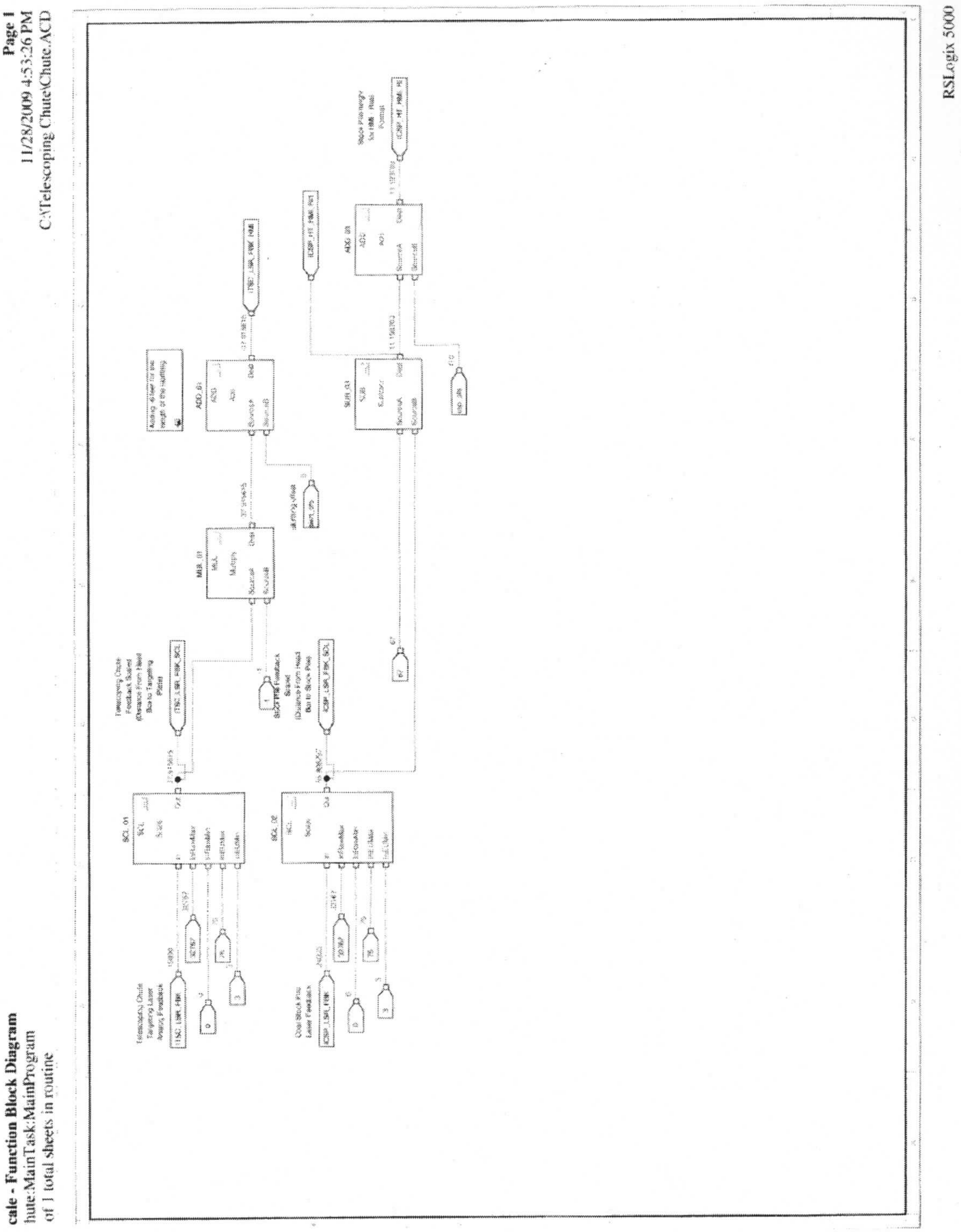
B - 29: General IO Routine

Appendix B (Continued)



B - 30: Scaling Input Routine